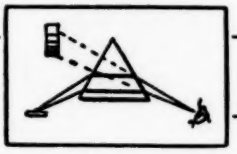
Journal of the OPTICAL SOCIETY *of* AMERICA

VOLUME 38
No. 1



JANUARY
1948

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Published monthly
at Prince and Lemon Sts., Lancaster, Pa.
by the
AMERICAN INSTITUTE OF PHYSICS
Incorporated
57 East 55 Street, New York 22, New York
FOR AND UNDER THE EDITORIAL SUPERVISION OF THE
OPTICAL SOCIETY OF AMERICA

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA

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An **abstract** must accompany each article. It should be adequate as an index and as a summary.

All but the simplest **mathematical expressions** should be carefully printed in by hand. Be sure to distinguish between capital and small letters. Indicate clearly superscripts and subscripts by inverted carets and carets, respectively. Avoid complicated superscripts and subscripts. Avoid repetition of a complicated expression by representing it by a symbol. Identify in the margin Greek letters and unusual symbols. Use fractional exponents instead of root signs. Use the solidus (/) for fractions wherever its use will save vertical space.

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Elsewhere **$7.70**

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Subscriptions, renewals, and orders for back numbers should be addressed to Prince and Lemon Streets, Lancaster, Pennsylvania, or to the American Institute of Physics, 57 East 55 Street, New York 22, New York.

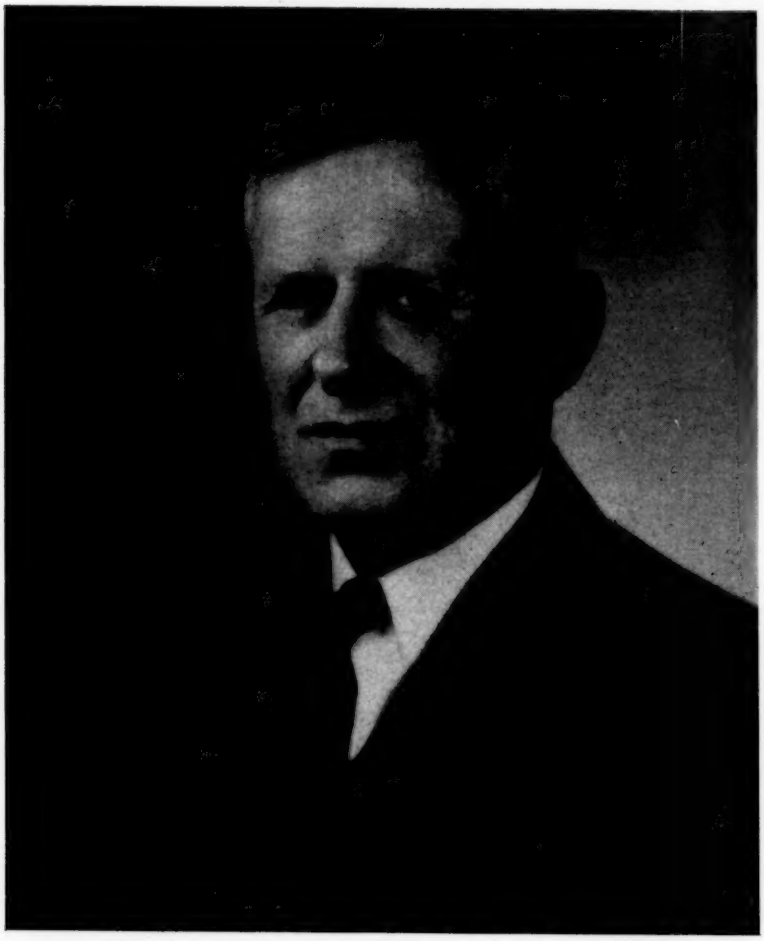
The *Journal of the Optical Society of America* is published monthly at Prince and Lemon Streets, Lancaster, Pennsylvania.

Entered as second-class matter March 22, 1933, at the Post Office at Lancaster, Pennsylvania, under the Act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, section 538, P. L. and R., authorized March 22, 1933.

The Frederic Ives Medal for 1947

Awarded by The Optical Society of America to William Frederick Meggers
for distinguished work in optics.

This medal, awarded biennially, was endowed in 1928 in honor of Frederic Ives, distinguished for his pioneer contributions to color photography, photo-engraving, three-color process printing, and other branches of applied optics.



Harris and Ewing

Dr. W. F. Meggers

Journal of the
OPTICAL SOCIETY
of AMERICA

VOLUME 38, NUMBER 1 JANUARY, 1948

Dr. W. F. Meggers

Ives Medalist for 1947

AT its Cincinnati meeting in October, 1947, the Optical Society of America awarded the Frederic Ives Medal to Dr. William Frederick Meggers, Chief of the Spectroscopy Section of the National Bureau of Standards.

This medal is awarded biennially for distinguished work in optics, and its past recipients have been as follows:

In 1929, Edward Leamington Nichols;
In 1931, Theodore Lyman;
In 1933, Robert Williams Wood;
In 1935, George Ellery Hale;
In 1937, Herbert Eugene Ives;
In 1939, August Herman Pfund;
In 1941, Selig Hecht;
In 1943, Loyd Ancile Jones;
In 1945, William Weber Coblentz. .

The presentation of the medal to Dr. Meggers took place in the Pavillon Caprice of the Netherland Plaza, and was followed by an address by Dr. Meggers.

Presenting Dr. Meggers, Dr. Paul E. Klopsteg, Chairman of the Committee appointed to nominate a candidate for the award, spoke as follows:

"The Frederic Ives Medal Committee, consisting of Messrs. Wallace Brode, the late Selig Hecht, David L. MacAdam, and A. H. Pfund, serving with the chairman, made a conscientious review of the names of numerous persons whose achievements in optics left no question as to their eligibility for this award of distinction. There was discussion by letter, and this was followed by a number of mail ballots, first to narrow the field, finally to achieve unanimity. The fact that the membership of the Committee included two Ives medalists gave it special qualifications to undertake its assignment. The Committee now takes pleasure in reporting to you and to the Society that it unanimously nominates William Frederick Meggers for the award by this Society of the Frederic Ives medal.

"On behalf of the Committee I should like to take a moment to give recognition to the interested and effective participation in its work by its late member and distinguished scholar and Ives medalist, Dr. Selig Hecht, and to express the sorrow of his colleagues that his sudden and unexpected passing deprives them of the pleasure and stimulation of his presence, the Society of a distinguished member, and science of one of its most competent contributors.

"Dr. Meggers has devoted a third of a century to sustained, intensive, and productive activity in atomic spectroscopy. This unremitting interest and its fruitful results provide a strong and insistent suggestion that we confer upon him another nomination, namely, Dean of American Spectrographers.

"In preparing this presentation address, the obvious procedure was to search the record for the accomplishments of the nominee. These were so voluminous, so overwhelming, that the writer could not help but wonder whether there were anything that might qualify our nominee for membership in what Bert Leston Taylor once

called the so-called human race—whether there were no weak points in this armor of distinction. An effort to find evidence of this sort by consulting with the members of the Committee and others resulted in failure. Those who know Dr. Meggers will require no evidence or proof of his fine human qualities. One of his associates terms him a meek but devastating wit, and the only spectroscopist who can "sass" President Harrison with impunity—a fact which for years has enlivened spectroscopy conferences and Optical Society meetings. His extracurricular interests are wide. Indian relics and music are illustrative. His Museum for Science and Civilization, established at his home, is noteworthy. We like him for his human qualities and honor him for his notable accomplishments in optics.

"One of Dr. Meggers' early papers, in collaboration with C. G. Peters, has remained to this day a work of the greatest importance in spectroscopy. Published in 1918, it reported 'Measurements on the Index of Refraction of Air for Wave-lengths from 2218A to 9000A.' This work was responsible for the tables which are used by every spectroscopist who needs to convert wave-lengths to wave-numbers—the basis of modern spectroscopy. Since practically all wave-lengths are measured in air, it is necessary first to convert them to their value in vacuum to permit accurate determination of the frequency of the light emitted by atoms in molecules. Although there has always been some uncertainty as to the precise figures, the values of Meggers and Peters are the ones used. It may turn out that the discrepancies arise from the constitution of the air in which measurements are being made.

"It would unduly extend this program were one to try to present a detailed review of all the important work for which we are now honoring Dr. Meggers. We shall only touch upon a few of the accomplishments of the medalist that are recorded in the papers of which a bibliography is appended. This extends into the fields of spectroscopy, physical optics, astrophysics, and photography. He has made important contributions to the knowledge of spectra of more than half of all the known elements. He has had outstanding success in identifying the spectral terms responsible for a phenomenal number of the spectral lines he measures. He was among the first to photograph infra-red emission spectra and was the first to do so for wave-lengths greater than one micron. He has made many interferometric measurements of wave-lengths throughout the spectral range for the establishment of secondary standards.

"He has a broad perspective of the entire field of atomic structure and a keen realization of the needs of science in this field. He is held in highest esteem by the student of fundamental spectroscopy and atomic structure, and by the user of spectroscopic methods for quantitative and qualitative analysis.

"Dr. Meggers is an alumnus of Ripon College, obtained his Master's degree at the University of Wisconsin, was instructor in physics at Carnegie Institute of Technology, and received the Doctor's degree at Johns Hopkins. Since 1914 he has been physicist at the National Bureau of Standards, and he has been chief of the spectroscopy section since 1920. Although his position at the Bureau has, in a measure, isolated him from teaching, he has nevertheless been an important figure in education and training in his field through the many people from the educational institutions who have worked under his direction at the Bureau of Standards. Through them he has made important contributions to numerous college and university laboratories.

"Mr. President, the Committee considers it a great privilege to present William Frederick Meggers as the nominee for the Frederic Ives Medal of the Optical Society of America."

The Frederic Ives Medal was then presented to Dr. Meggers by President George R. Harrison.

On presentation of the medal, Dr. Meggers replied as follows:

"President Harrison and Members of the Optical Society of America:

"I am completely overwhelmed. I hardly know what to say. In such circumstances it is customary to say that words fail or are inadequate to express one's feelings. That is certainly true in this instance.

"Although I have known of the Frederic Ives medal since its foundation in 1928, and actually witnessed the first and last two awards, it never entered my head, believe it or not, that I would

ever be a candidate for this honor. Consequently, when President Harrison officially informed me that this medal would be bestowed upon me at this meeting I was taken completely by surprise. I felt both flattered and embarrassed—flattered to think that the award committee regarded my work in optics as distinguished, and embarrassed because I couldn't remember doing any distinguished work in optics. I am relieved, happy, and grateful that Dr. Klopsteg has tried to clear this up for all of us. Of course, no one is required to believe every word of the citation but why should *I* question the veracity of Dr. Klopsteg?

"Last week I completed exactly one-third of a century in the Spectroscopy Section of the National Bureau of Standards. If I have accomplished anything worth while in that period it was partly because I had to earn a living and partly because of fortunate circumstances. It seems to me that luck often deserves most of the credit for human successes. At least this *must* be true in any case because I was handicapped in the beginning by being born on Friday, the thirteenth!

"Thus, I certainly was lucky to start a career in spectroscopy a few months after Bohr published his celebrated postulates which mark the beginning of the quantum theory of atomic spectra. Again, I was fortunate to come under the tutelage of Dr. Keivin Burns, who taught me how to photograph spectra, measure wavelengths, and make spectrochemical analyses.

"It was lucky too that I stuck to spectroscopy day and night for 33½ years, without being tempted to abandon or neglect it for mere money.

"It was my good fortune also to be endowed with a rugged constitution so that I could work years on end without vacations and a third of a century with a total of 2 days sick leave.

"Finally, I have always been blessed with the best cooperation that any one could wish for, and my associations with fellow workers throughout the world have supplied inspiration through the years. With your permission I should like to have each and every one of my co-workers feel that they are sharing in the great honor you have bestowed upon me.

"The combination of all these lucky circumstances explains my contributions to standard wave-lengths, descriptions of atomic and molecular spectra, classifications of spectral lines, and spectrochemical analysis—mostly tedious, painstaking tasks that you have been kind enough to label 'distinguished work in optics.' If I wished, I could recite also a list of unlucky circumstances which gave negative results for many experiments, prior publication to some competitors, and the discovery of fundamental principles to others endowed with greater perspicacity. However, I am certain that my good fortune has always preponderated, and now to climax it all I have been lucky to receive the greatly prized Frederic Ives medal.

"The Frederic Ives medal is, in my opinion, the greatest honor that can come to a spectroscopist. This public expression of your appraisal and approval of my 'distinguished work in optics' makes me want to do better than ever, and I trust that you will not be disappointed with my future work. In accepting this Frederic Ives medal I sincerely thank you, Mr. President, and you, the Award Committee, and you, the members of the Optical Society of America, who elect officers who appoint committees who award medals. I thank you all from the bottom of my heart."

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(2) "Interference measurements of wave lengths in the iron spectrum (3233–6750A)" (with K. Burns and P. W. Merrill), Sci. Pap. Bur. Stand. **13**, 245–272 (1916).

(3) "Wave-length measurements in spectra from 5600A to 9600A," Sci. Pap. Bur. Stand. **14**, 372–395 (1917).

(4) "The properties and testing of optical instruments," Circular Bur. Stand. No. 27, 1–41 (1918).

(5) "Photography of the solar spectrum from 6800A to 9600A," Astrophys. J. **47**, 1–6 (1918).

(6) "Wavelengths in the red and infrared spectra of iron, cobalt, and nickel arcs" (with C. C. Kiess), Sci. Pap. Bur. Stand. **14**, 637–651 (1918).

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JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 1 JANUARY, 1948

A Light Wave of Artificial Mercury as the Ultimate Standard of Length

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SO far as I have been able to determine, the suggestion that a light wave could serve as a constant, reproducible standard of length was first made one hundred and twenty years ago (1827) by the French natural philosopher, Jacques Babinet.[1]

In 1839, the German astronomer, Johann Lamont,[2] suggested that diffraction of sunlight provided an exactly reproducible unit of length in the wave-length of Fraunhofer's *D* line.

In 1870, the British physicist, J. C. Maxwell[3] suggested that the wave-lengths of hydrogen must be invariable, and therefore better suited than the earth as a standard of length.

In the same year, a Dutch physicist, V. S. M. van der Willigen[4] discussed the difficulties and errors inherent in the use of a second's pendulum as a natural standard of length, and proposed that the sodium lines be adopted as standard.

It appears that van der Willigen was the first to suggest that a length could be determined in terms of light waves by counting Newton's rings of sodium light displaced by a slow approach of a plane glass toward a convex one; he regretted

* Address delivered by the recipient of the Frederic Ives medal on the occasion of its presentation at the Thirty-second Annual Meeting of the Optical Society of America, Cincinnati, Ohio, October 24, 1947.

[1] J. Babinet, Ann. chim. phys. **40**, 177 (1829). "Si la terre était jamais choquée par une comète, son axe de rotation et sa forme changeraient indubitablement, et dès-lors les mesures du pendule ou de l'arc du méridien ne seraient plus propres à faire retrouver le mètre. Cette question spéculative ayant été un jour débattue à Paris dans une réunion scientifique, Sir Humphrey Davy proposa un étalon, qui, suivant lui, pourrait être retrouvé après les plus fortes altérations dans la forme du globe: son unité linéaire aurait été le *diamètre* du tube capillaire de verre dans lequel l'ascension *de l'eau* serait exactement égale à ce même diamètre. En songeant à toutes les difficultés de l'expérience, j'indiquai, à mon tour, les mesures de la longueur des ondulations lumineuses *dans le vide*, comme une méthode qui conduirait plus sûrement au même but."

[2] J. Lamont, Jahrbuch der König. Sternwarte bei München, **3**, 188 (1839). "Wünchte Jemand z.B. in Amerika, wo eine authentische Copie des *mètre* nicht ohne Kosten und Zeitverlust zu erhalten wäre, die genaue Länge dieses Maases zu wissen, so hätte er nur durch Zusammenstellung zweier Micrometerschrauben von gleichem Gewinde, oder durch Übertragen der Gänge einer Micrometerschraube auf Glas ein Gitter zu bilden, und fände er z.B., dass durch sein Gitter die Linie D im ersten Spectrum einen Abstand von 4′ 30″ erhielte, so könnte er sagen, dass 2223¼ Umgänge seiner Micrometerschraube der Länge des Mètre gleich seyen." (p. 209).

Theoretisch betrachtet würde es zweckmassiger gewesen seyn, die Länge, welch als Constante bei den Diffractions-Phänomenen vorkommt, nämlich die Länge einer Lichtwelle, zur Maassbestimmung zu wählen.

Nimmt man wiederum den Theil des Spectrums, welcher der Linie D entspricht, so hat man

1 Pariser Fuss = 551724 Wellenlangen
1 Metre = 169845 Wellenlangen
1 Bayer. Fuss = 495712 Wellenlangen
1 Engl. Fuss = 517678 Wellenlangen

Da man indessen die Wellenlänge nicht unmittelbar beobachten kann, sondern sie erst aus dem Ablenkungswinkel zu berechnen hätte, so scheint es geeigneter, die Maassbestimmung mit dem Winkel selbst zu verbinden." (p. 212).

[3] J. C. Maxwell, Rep. Brit. Ass., Not. and Abstr., p. 7 (1870). "The earth has been measured as a basis for a permanent standard of length, and every property of metals has been investigated to guard against any alteration of the material standards when made. . . . Yet, after all the dimensions of our earth and its time of rotation, though, relatively to our present means of comparison, very permanent, are not so by any physical necessity. The earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before. But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen. If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wave-length, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules."

[4] V. S. M. van der Willigen, Archives Musée Teyler **3**, 142 (1870). "Dans cet état des choses, il peut y avoir de l'utilité à attirer l'attention sur une autre grandeur existant dans la nature, grandeur qui partout et toujours se trouve à notre portée, qui en tout temps et en tous lieux à la même longueur, et qui est entièrement indépendante de bornes placées à la surface de la terre ou de mesures astronomiques. Cette grandeur, c'est la longueur d'ondulation de la lumière du sodium, ou, pour parler plus exactment,—attendu que la ligne spectrale jaune de cette lumière ne tarde pas à se dédoubler quand la dispersion est un peu considérable,—c'est la longueur d'ondulation moyenne de la lumière du sodium, réduite, bien entendu, au vide. En quelque endroit de la terre qu'on se trouve, aujourd'hui et dans des milliers d'années, aussi longtemps qu'on aura un grain de sel de cuisine à sa disposition, on pourra déterminer les longueurs d'onde de ces deux vibrations, en prendre la moyenne et s'en servir pour vérifier les étalons de mesures." (p. 159).

"Ma première idée fut de recourir à la méthode employée par M. Fizeau pour déterminer la dilatation du verre, du quartz et d'autres matières analogues. Je voulais, de même que ce savant, opérer un rapprochement graduel entre un verre plan et un verre convexe, et compter le nombre des anneaux de Newton déplacés dans la lumière homogène du sodium; du rapprochement connu des verres on aurait conclu la longueur d'onde, puis, par le déplacement de quelques milliers d'anneaux, on aurait obtenu, en y mettant beaucoup de patience et une grande application, une longueur matérielle égale à un nombre connu de longueurs d'onde." (p. 161).

that this method was not practical at the moment and contented himself with measurements on three plane gratings from which he deduced the approximate number of sodium yellow waves in a meter.

A. A. Michelson and E. W. Morley[5] were the first to devise a practical method of applying optical interference phenomena to length measurements. In 1887 they outlined "a method of making the wavelength of sodium light the actual and practical standard of length." Their method involved the use of the interferometer devised by them for their celebrated experiments on the relative motion of earth and ether; it consisted of a measurement of a length and the counting of an equivalent number of interference fringes. That paper also contained the first reference to the observed duplicity of the red radiation from hydrogen; the disappearance of interference at retardation of 15,000 and 45,000 waves indicated a double line with components about one-sixtieth as far apart as the sodium yellow lines.

Two years later, in a paper entitled "On the feasibility of establishing a light wave as the ultimate standard of length," Michelson and Morley[6] described the method later used in measuring the meter, and reported the first interferometer values of wave-lengths for one sodium line, one lithium line, and three mercury lines. Significant references to radiation from mercury are found in the following quotations:

> "In the problem of making a light wave a practical standard of length, it is desirable to use as an intermediate standard a metal bar bearing two plane surfaces at the greatest distance apart at which interference (between two pencils having this difference of path) is accurately measurable. Some preliminary experiments have shown that in the case of a green mercury wave the distance may be a fourth of a meter." (p. 181).
>
> "The yellow mercury light has the inconvenience of being double; but the two radiations are of nearly equal intensities. When, however, the phase-difference amounts to nearly half a wave it may be necessary to add or subtract half a wave from the observed result. The brilliant *green* (mercury) line gives beautifully clear circles even with a difference of path of half a million waves, so that in all probability *this will be the wave to be used as the ultimate standard of length.*" (p. 183).

[5] A. A. Michelson and E. W. Morley, Am. J. Sci. **34**, 427 (1887).

[6] A. A. Michelson and E. W. Morley, Am. J. Sci. **38**, 181 (1889).

In his second paper "On the application of interference methods to spectroscopic measurements" Michelson[7] reported "visibility curves" for lines of oxygen, sodium, zinc, cadmium, thallium, and mercury. This marks the discovery of spectral-line hyperfine structure, and the abandonment, at least temporarily, of the mercury green line (5461A) as the ultimate standard of length. "The green mercury line is one of the most complex yet examined." (p. 292). We can easily imagine Michelson's disappointment in making this discovery which disqualified the green line from natural mercury as the ultimate standard of length. "One of the purposes which led to these investigations was the search for a radiation of sufficient homogeneity to serve as an ultimate standard of length. . . . The red cadmium line is almost ideally homogeneous, and will readily permit the estimation of a change of phase in the interference fringes of one hundredth of a fringe in a total distance of 200 millimeters, or over 300,000 waves." (p. 298).

These classic investigations led promptly to Michelson's invitation to the International Bureau of Weights and Measures, where (in 1892) he performed his celebrated experiment by which he determined the number of red waves of cadmium in one meter.

Up to the time of Michelson's classic investigations all spectral lines were regarded as monochromatic and immutable, except that an apparent change in wave-length due to relative motion of light source and observer in the line of sight was suggested by Doppler in 1842. Naturally, the Doppler effect vanishes when the light source and observer are stationary, as is usually the case in a laboratory. However, the kinetic energy of the individual radiating particles gives all spectral lines a Doppler width which usually delimits the monochromaticity. In fact, at low pressures, and in the absence of strong electric fields, the widths of spectral lines are fully accounted for by the Doppler effect of the light-emitting particles. In wave-length units these widths are proportional to $\lambda(T/M)^{\frac{1}{2}}$, where λ is the mean wave-length, T the absolute temperature, and M the atomic weight. In other words, the most monochromatic spectral lines are emitted by massive slow-moving atoms, and

[7] A. A. Michelson, Phil. Mag. **34**, 280 (1892).

because mercury atoms are nearly twice as heavy as cadmium atoms and can be excited to radiate at less than half the absolute temperature, mercury lines are only half as wide as cadmium lines, other things being equal.

The hyperfine structures discovered by Michelson were the subject of investigation and speculation for nearly forty years before they were finally satisfactorily explained as consequences of nuclear masses and momenta. Because the effective wave-length of a complex line observed interferentially varies with the phase relations of the various components, and because the relative intensities of the components may vary, it is imperative to avoid lines with hyperfine structure in selecting a natural standard of length. However, the mere presence of more than one isotope, or of one or more nuclei with spin momenta, does not necessarily condemn all spectral lines. Thus, despite the fact that cadmium has eight isotopic forms and two nuclear spins, no isotopic or hyperfine structure has been resolved in Michelson's red line, although it is readily observed in other cadmium lines. Natural mercury exists as a mixture of seven isotopes, two with spins, but no line of ordinary mercury has been found free of structure. In 1931 I suggested that sharp lines could be obtained from an even-mass isotope of mercury if such an isotope in sufficient quantity could be separated from the rest by the mass spectrometer. Nothing ever came of this suggestion because adequate separation of mercury isotopes was much too expensive.

In his investigations of line structure Michelson[7] observed that "the effect of temperature and of pressure on the visibility may be readily accounted for on the kinetic theory. In fact, there is but little doubt that these are the chief if not the sole causes of the broadening of spectral lines and the consequent diminution of visibility; the latter cause acting by altering the period of the source by frequent collisions, and the former, by the change in wave-length of the light due to motion of the source in the line of sight." (p. 293). The later work by W. J. Humphreys and J. F. Mohler[8] proved that an increase in pressure not only broadens the spectral lines but also produces dissymmetry and displacement toward longer waves.

The only other effective cause of line dissymmetry and displacement is the Stark effect discovered in 1913. Unlike the magnetic splitting of spectral lines (Zeeman effect) which is, in general, perfectly symmetrical and in ordinary light sources, quite inappreciable, the electric splitting or displacement is usually unsymmetrical and easily confused with pressure effect. In light sources the electric fields may be due to applied potentials or to a high density of electrons or ions in the discharge.

Although these major causes, pressure effect and Stark effect, of spectral line displacement were unknown in 1892, Michelson intuitively avoided them by operating his light sources at low pressures and small current densities. Today, fifty-five years later, we stand in admiration of his amazing skill in choosing with his primitive interferometer the cadmium red line as an ultimate standard of length, and after searching all spectra with improved apparatus we must admit that he selected the best line in nature.

Michelson's classic experiment by which he determined the relation between the meter and the cadmium red wave-length has been repeated a half dozen times and his result has been amply confirmed.[9]

In 1907 the International Union for Cooperation in Solar Research adopted as a definition of the angstrom unit of wave-length the value of the cadmium red wave 6438.4696A observed by Benoit, Fabry, and Perot in 1906. This value was accepted in 1922 by the International Astronomical Union, successor to the I.U.C.S.R., which was a casualty of World War I. Those old enough to remember that world calamity will recall the anxiety and fear that a bomb might accidentally destroy the world's prototype meter near Paris. The only way to circumvent such a disaster is to substitute for the perishable meter an indestructible but accurately and easily reproducible wave-length as the ultimate standard of length.

In 1927 the National Bureau of Standards recommended[10] that the International Confer-

[8] W. J. Humphreys and J. F. Mohler, Astrophys. J. **3**, 114 (1896).

[9] J. E. Sears, Sci. Prog. **31**, 209 (1936).

[10] Proces. Verbaux Seances Con. Int. Poids Mesures, 12, 64, 1927. "On recommande que la Conférence adopte la

ence of Weights and Measures adopt the wave-length of red radiation from cadmium vapor as the primary standard of wave-length, and that *the meter be defined in terms of this wave-length.*

The ultra-conservative Conference objected[11] that such a definition of the meter would menace the metric system, and explained that it was not a question of giving a true relation between the meter and the wave-length, but only a metric value of the latter which could be modified by future experiments. Consequently, the resolution actually adopted stated specifically that the value of the meter expressed *in a provisional manner* in wave-lengths of the red ray of cadmium was 1553164.13. Presumably, if a different value is found in the future, the meter must be assumed to be immutable, and either the wave-length or the angstrom must be changed. Strictly speaking, the world's primary standard of length is still the distance, adopted in the 18th century, between two scratches (6 to 8 μ wide) on a platinum-iridium bar at the International Bureau near Paris, despite the fact that practically all precise measurements of lengths in the 20th century have been made, and will continue to be made, with light waves.

The earth has thus far escaped collision with a comet, and the prototype meter has survived the bombs of two World Wars, but who will be foolhardy enough to predict that the meter will not be atomized by the atomic bombs of World War III? As if to make amends for such a catastrophe the atomic scientists have already provided a superior future ultimate standard of length. And who will weep over the loss of an arbitrary, archaic measuring stick when a better standard, meeting the scientific specifications of today and tomorrow, has become available? The same atomic research and nuclear engineering that produced the atomic bomb and put the meter in greater jeopardy, also provided the methods and means for large scale transmutations and manufacture of pure elements not found in nature. In particular, it is now possible to make any desired quantity of absolutely pure mercury from gold (alchemy in reverse), and thus obtain material for a spectroscopic light source emitting wave-lengths more than twice as sharp as the best emitted by natural elements.

The nuclear reaction which transmutes gold to mercury was first reported in 1934 by Fermi, *et al.*[12] who used a mixture of beryllium powder and radon as a neutron source to bombard gold. Neutrons that attach themselves to nuclei of gold atoms produce a highly radioactive isotope of gold which decays rather rapidly by β emission (half-life 2.7 days) and becomes a stable isotope of mercury:

$$^{79}Au^{197} + {}^{0}n^{1} \rightarrow {}^{79}Au^{198} + {}^{-1}\beta^{0} \rightarrow {}^{80}Hg^{198}.$$

In 1940 Wiens and Alvarez[13] reported that bombardment of gold by neutrons from a 60-inch cyclotron produced sufficient mercury to give a light source that emitted spectral lines entirely free from hyperfine structure. Exposure of one ounce of gold to neutrons for one week made enough mercury to be identified spectroscopically in a tiny electrodeless lamp that lived about one minute. One month of exposure yielded enough mercury to operate a lamp for about five minutes and obtain the first Fabry-Perot spectrogram. Ten months exposure near the cyclotron produced a discharge tube that ran for more than thirty minutes.[14] At this rate it would require one thousand years to produce one Hg^{198} lamp with a useful life of one thousand hours.

At a spectroscopy conference in Chicago in 1942, I discussed[15] the primary standard of wave-length, and called attention to the theoretical advantages of the mercury green as compared with the cadmium red line, especially if sufficient Hg^{198} were available.

In 1942, Dr. L. J. Briggs, then Director of the National Bureau of Standards, approved the purchase of forty ounces of proof gold, and enlisted the cooperation of the University of California to expose this gold to neutrons for one or more years. The assumption was that if a useful mercury lamp could be obtained from

longueur d'onde de la radiation rouge émise par la vapeur de cadmium, determinée par Benoit, Fabry, et Perot, comme étalon fondamental pour la longueur des ondes lumineuses. . . . Le mètre doit être défini par la relation: 1 mètre = 1553164.13 longueurs d'onde du rayonnment rouge du cadmium, dans les conditions normales spécifiées."

[11] Trav. Mem. Bur. Int. Poids Mesures **18**, 53 (1930).

[12] E. Fermi, E. Amaldi, O. D'Agostino, F. Rasetti, and E. Segrè, Proc. Roy. Soc. **146A**, 483 (1934).

[13] J. H. Wiens and L. W. Alvarez, Phys. Rev. **58**, 1005 (1940).

[14] J. H. Wiens, Phys. Rev. **70**, 910 (1946).

[15] W. F. Meggers, Rev. Mod. Phys. **14**, 59 (1942).

one ounce of gold, forty ounces might produce forty lamps of the same kind, or perhaps several of much greater efficiency. Unfortunately, World War II interrupted the experiment and only sub-microscopic quantities of artificial mercury were made. Several tiny discharge tubes were prepared in 1943, but in size, brightness, and life they were reminiscent of sick fireflies, and had no practical value. The prospects were very discouraging when, near the end of the war, there were rumors of a secret source of neutrons thousands of times more effective than the largest cyclotron. One day a dirty gold bar with a secret history was delivered to us carefully wrapped in oily paper. The gold was said to contain Hg^{198}. Successive heatings, pumpings, and sealings of condensable vapors in glass tubes finally yielded one lamp which emitted a spectrum of mercury lines without hyperfine structure. This lamp was excited with 110 mc radio waves; it was used mainly for demonstrations, and had a total life of about fifty hours before it succumbed to clean-up.

Experiments with lamps containing micrograms, or even some milligrams, of mercury show that clean-up effects of the electrical discharges seriously limit the useful life of such lamps. In electrodeless tubes the discharges gradually drive the mercury into the glass and blacken the walls of the tube. In lamps with internal electrodes the electrodes, either as such or in the process of sputtering, tend to swallow up the mercury until no vapor remains.

In 1945 the National Bureau of Standards gold was transferred from California to Tennessee. The treatment this gold received was not disclosed but a year later we distilled from it about 60 milligrams of mercury. With only 60 mg of Hg^{198} on hand, and the prospect of numerous demands for lamps, it was necessary to contract for larger amounts of Hg^{198}, and also try to design satisfactory lamps with minimum clean-up losses of precious material.

Last July, Dr. E. U. Condon, the present director of the National Bureau of Standards, requested the Atomic Energy Commission to bombard some more gold with neutrons. The time, place, and manner of treatment are all secret, but we expect to have approximately two grams of artificial mercury within a year. Meanwhile, experiments are being made with natural mercury and with 60 mg of Hg^{198} to arrive at spectroscopic light sources that will be satisfactory for accurate measurement of wave-lengths.

In the design of a Hg^{198} lamp that will emit radiations suitable as ultimate standards of length a maximum is desirable in each of the following five characteristics: (1) monochromaticity, (2) reproducibility, (3) intensity, (4) life, and (5) convenience. It is perhaps obvious that some of these requirements conflict with others, and that, in general, it will be necessary to make compromises.

(1) Monochromaticity or sharpness of spectral lines depends on operating conditions of the light source as well as upon certain atomic properties already mentioned. To obtain narrow lines with atoms of given mass it is necessary to limit Doppler broadening due to high temperature; pressure, collision, and resonance broadening due to high gas or vapor density; Stark broadening due to large gradients in electrical potential; and interatomic Stark broadening due to high current density in the discharge. In other words, the source should function at low temperature, at low pressure, with moderate applied voltage, and with low current density. Some sharpness must be sacrificed if high intensity is imperative.

(2) Reproducibility of wave-lengths emitted by a light source rests upon constant gas or vapor pressure, upon low current density, and upon the absence of self-reversal and hyperfine structure. Changes in pressure are always accompanied by small changes in wave-lengths, and interatomic Stark effects from high currents always displace lines unsymmetrically. For example, it has been shown[15] that currents of 2.5 and 5.0 amperes in cadmium metal vapor arcs increase the wave-length of the red line by 0.0003 and 0.0007A, respectively. Self-reversal is often unsymmetrical, but even if it is symmetrical it is undesirable, because it reduces the intensity and may lead to misinterpretation of interference patterns. Self-reversal is inappreciable if lines ending on the ground state are avoided, or if a constricted discharge is viewed side-on instead of end-on. There is some evidence that relative intensities of hyperfine structure

change with operating conditions of the light source, and ample proof that unresolved hyperfine structure falsifies the true wave-lengths of spectral lines.

(3) Intensity or brightness of a metal vapor lamp is a function mainly of the current per unit cross section of the discharge. This can be increased either by reducing the resistance of the circuit to boost the current, or by reducing the cross-section of the discharge by a constriction, or by viewing a long column of luminous vapor end-on. In general, however, a high current density is accompanied by increased temperature and pressure, and by interatomic Stark effect, all of which entail line broadening. For these reasons the current is restricted to seven milliamperes per square millimeter in the operation of the Michelson lamp to produce the cadmium red primary standard.

The self-broadening effects (due to the atoms of the same kind as those radiating) are in some cases greatly reduced by admitting a few millimeters (Hg) pressure of noble gas since the pressure effects of a foreign gas are much smaller than those of the diluted vapor, and collisions of the second kind with noble gas ions greatly increase the intensity of light emitted.

Usually the highest intensity is obtained from hot-cathode arc discharges but if the current is reduced sufficiently to make line broadening and displacement negligible, the intensity advantage is lost. A similar intensity loss occurs if vapor pressure is reduced by drastic cooling to sharpen the lines. It is inevitable that high intensity must be sacrificed when monochromaticity and reproducibility are more important. The apparent intensities of some spectral lines are strikingly reduced by partial or complete self-reversal in the light source if the temperature or excitation is not uniform throughout.

(4) Barring accidents the useful life of a lamp containing a minute amount of gas or vapor is determined by the clean-up time. This is relatively short in electrodeless lamps excited by high-frequency discharges, which darken the walls of the lamp by driving the gas or metal atoms irretrievably into the glass walls. Lamps with internal electrodes also clean up charged gases and vapors either by adsorbing them or by trapping them in sputtered films of electrode material. The mechanism of clean-up is not fully understood and cannot be predicted for Hg^{198} lamps, but experiments are being made with small amounts of natural Hg and with lamps of different design and materials to determine the conditions that will guarantee a life of one thousand hours or more. If and when the amount of artificial mercury is produced in much larger quantities, the unavoidable clean-up losses will become less important. In my opinion this is a good argument for designing the next chain-reacting pile to be constructed to use gold instead of cadmium as a control element; the past and present use of cadmium produces no useful by-product like the transmutation of gold into Hg^{198}.

(5) Convenience of operation is an important factor in popularizing a spectroscopic light source and using it for precise measurements. Owing to the inconvenience of operating the standard cadmium lamp in a furnace, that source has rarely been used except for measuring the meter, and for the determination of some secondary standards of wave-length.

Although practically perfect monochromaticity is attained by viewing transversely a unidirectional atomic beam, such a source is much too inefficient and inconvenient to be considered in connection with an ultimate standard of length. Fairly intense spectra of very sharp lines are observed in cooled hollow cathode discharges but these sources also are so awkward to operate that their use has been confined almost exclusively to investigations of hyperfine structure by only the most skilled spectroscopists.

Enclosed mercury vapor arcs containing hot cathodes operate on applied voltages of commercial circuits and are unsurpassed for convenience, brilliance, and life, but they require more than a few milligrams of mercury, and sacrifice monochromaticity and reproducibility for intensity.[15] Such sources cannot be recommended as an ultimate standard, but they will certainly be employed whenever convenience and intensity are the most important considerations.

The ultimate in simplicity of construction is found in the electrodeless discharge tube which is made by sealing small amounts of gas or

vapor in evacuated tubes of glass or quartz. Formerly the excitation was provided by high frequency Tesla discharges but in recent years these have been replaced by simple and convenient radio-frequency generators of very short waves. By this method intense light emission can be obtained from vapors at extremely low pressures, but the operating pressures are rather critical. A serious fault of this type of source is the relatively rapid clean-up action resulting from penetration of vapor particles into the walls of the tube.

It appears that the most convenient and practical light source for an ultimate standard of length is the Geissler tube originally made for producing spectra of gases at reduced pressures. Michelson's cadmium lamp is in reality a Geissler tube but the necessity of inclosing it in a furnace maintained at a temperature of 300° to 320°C entails unwanted Doppler broadening as well as inconvenience. Because mercury has an appreciable vapor pressure even at temperatures below zero centigrade it can be excited to emit sharp lines in Geissler tubes. These tubes are normally operated with cold cathodes and can be air-cooled or water-cooled if so desired. They require an applied potential of only a few thousand volts and a current of some milliamperes; their convenience, durability, and efficiency are partly responsible for the ubiquitous luminous signs.

In October 1947, I prepared an electrodeless lamp in Pyrex glass and Dr. N. C. Beese of the Westinghouse Electric Corporation prepared two lamps of Vycor glass with internal electrodes of molybdenum. Each of these lamps contains 5 milligrams of Hg^{198} and 5 millimeters (Hg) pressure of argon gas. Lamp blanks of vycor glass and of fused quartz have also been made with zirconium electrodes, and capillary designed for water cooling and for either side-on and end-on viewing. The operating characteristics of these experimental lamps will be investigated to determine which, if any, may be recommended as a satisfactory source of the ultimate standard of length.

Employing a Fabry-Perot interferometer with a 25 mm etalon preliminary values of the wavelengths of a dozen Hg^{198} lines, ranging from 3341 to 5791A, have been determined relative to the primary standard of wave-length. Publication of the observed wave-lengths of Hg^{198} will be deferred until final values are in hand. It suffices at this time to say that the preliminary values, when tested by the combination principle of spectroscopy, appear to be correct within one part in twenty million, whereas the best measurements made with natural mercury exhibit deviations of one part in one hundred thousand, due, no doubt, to the falsification of the wavelengths by unresolved hyperfine structure.

SUMMARY

The proposal that a wave of light constitutes a natural, reproducible standard of length has been traced from its origin with Babinet in 1827 to the present time. In 1889 Michelson and Morley stated that in all probability the mercury green line will be the wave to be used as the ultimate standard of length. However, in 1892, Michelson discovered that this line was complex and ineligible as a standard, whereupon he made the first accurate determination of the meter in wave-lengths of cadmium red light. Subsequent spectroscopic research indicated that this was probably the sharpest spectral line to be found in nature, and in 1927 the International Conference on Weights and Measures provisionally adopted a relation between the meter and this wave-length.

Because mercury is unique among the elements in radiating, at low pressure and temperature, a simple spectrum of extremely sharp lines, the mercury line rejected by Michelson would be superior to the cadmium line chosen providing a single even-mass isotope of mercury could be isolated or manufactured. The practicability of extracting pure Hg^{198} from gold bombarded by neutrons from a cyclotron was demonstrated by Wiens and Alvarez in 1940, but it was not possible in a reasonable time to make satisfactory lamps by this method. After 1945 gold bombarded by neutrons in a chain-reacting pile has been transmuted into Hg^{198} in sufficient quantity to make bright and durable lamps with which preliminary measurements of wave-lengths have been made relative to the primary standard with an accuracy one hundred times greater than that attainable with natural mercury. The most desirable characteristics of a standard light

source have been discussed under monochromaticity, reproducibility, intensity, life, and convenience. The future availability of satisfactory lamps emitting superior standards of length will be assured by the transmutation of more Au^{197} into Hg^{198} and by the improvement of lamp construction to reduce the clean-up. It seems certain that a progressive scientific world will eventually adopt the wave-length of green radiation (5461A) from Hg^{198} (and possibly 10140A for greater lengths) as its ultimate standard of length.

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 1 JANUARY, 1948

Algebraic Theory of the Primary Aberrations of the Symmetrical Optical System

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(Received July 18, 1947)

A concise, purely algebraic theory of the monochromatic primary aberrations of the symmetrical optical system is developed by means of a method depending on the consideration of quantities which reduce to optical invariants in the paraxial limit. The derivation of summation theorems is rendered superfluous. At every stage the order of the errors committed in the various approximations involved is considered in detail, with a corresponding gain in rigor. The equations for the final aberrations are derived in a well-known form. They contain aberration coefficients closely resembling the usual Seidel sums, and reducing to the latter when all the refracting surfaces are spherical. The increase in the labor involved in computing these more general sums is very small.

1. AN incidental result of an attempt by the author to develop a method of computing the exact higher order aberrations of symmetrical optical systems is a very simple algebraic derivation of the primary aberrations of such systems, resulting in a set of aberration coefficients very similar to the Seidel sums as customarily used in practice.[1] The development is short and transparent as compared, for example, to that given by Born.[2] It is here presented in the hope that it may be of value to the practical worker in this field who is not familiar with the method of Hamilton, in view of the increasing practical importance of systems containing aspherical surfaces it may be useful to realize that their primary aberrations can be written down and computed virtually as easily as the Seidel aberrations. Moreover, their theoretical derivation as presented below is shorter and certainly simpler than any other development of the Seidel sums known to the author.

A table of the more important symbols used in the text is appended in Section 9.

2. In view of the symmetry of the system we may take the object point to lie in the tangential plane. Then we associate with any refracting surface a left-handed Cartesian coordinate system such that its origin coincides with the pole A of the surface; the x axis lies along the axis of symmetry of the system, whilst the x, y plane coincides with the tangential plane. The y, z plane is then the tangent plane to the surface at A, and we may call this the polar-tangent plane. An arbitrary ray passing through the system will intersect the polar-tangent plane in the point whose y and z coordinates are Y, Z, respectively (before refraction at the surface); and α, $-\beta$, $-\gamma$ are the direction cosines of the ray. We then specify the incident ray at the surface by the four quantities Y, Z, V, W, where

$$V=\beta/\alpha, \quad W=\gamma/\alpha, \tag{2.1}$$

the corresponding quantities after refraction

[1] A. E. Conrady, *Applied Optics and Optical Design* (Oxford University Press, London, 1929), p. 314.
[2] M. Born, *Optik* (Julius Springer, Verlag, Berlin, 1933), Chapter II, pp. 23–31.

being distinguished by a dash. The *coordinates* of the ray are defined to be Y_1, Z_1, V_1, W_1.

To avoid unnecessary duplication of symbols and equations we shall use the convention that symbols in bold-face type shall stand for both the y and z "components" of the quantity to which it refers. Thus the coordinates of a ray are now written $\mathbf{Y}_1$, $\mathbf{V}_1$.

A tangential ray is specified simply by Y and V. When the latter are infinitesimal, so that we are dealing with a paraxial ray, we represent them by the small letters y and u; then, since each surface may be replaced by its tangent sphere in the neighborhood of the pole (*v.* Section 5), the ordinary paraxial theory holds, so that the relationship between y_i, u_j and y_1, u_1 is linear, i.e.,

$$y_j = y_{pj}y_1 + y_{qj}u_1, \quad u_j = u_{pj}y_1 + u_{qj}y_1, \tag{2.2}$$

the four constants in (2.2) being related by the identity

$$\begin{vmatrix} y_{pj} & y_{qj} \\ u_{pj} & u_{qj} \end{vmatrix} = \frac{N_1}{N_j}, \tag{2.3}$$

which is an expression of the Lagrange theorem.[3]

At any surface the equation of a ray before refraction may be written

$$\bar{x} = t, \quad \bar{y} = Y - Vt, \quad \bar{z} = Z - Wt, \tag{2.4}$$

where $\bar{x}$, $\bar{y}$, $\bar{z}$ are the current coordinates of points on the ray and t is a variable parameter. Now the position of the object point O_1 is specified by the distance l_{01} of its perpendicular projection O_{01} on the x-axis from the pole of the first surface, and its perpendicular distance ($= -h_1$, say) from the x axis. The point O_{01} has a series of conjugate ideal image points O_{01}', O_{02}', $\cdots$, O_{0k}' which define the positions of the ideal image planes after the respective surfaces, the jth plane of course being also the "ideal object plane" of the $(j+1)$th surface. All these planes are therefore uniquely determined once the path, taken by a single (tangential) paraxial ray through O_{01}, is known. Henceforth all quantities referring to such a ray will be distinguished by the subscript 0. At the jth surface, an arbitrary ray through O_1 will intersect the ideal object plane there in the point O_j the coordinates $-\mathbf{H}_j$ of which are given by (2.4) on putting $\bar{x} = l_{0j}$, i.e.,

$$\mathbf{H}_j = l_{0j}\mathbf{V}_j - \mathbf{Y}_j. \tag{2.5}$$

The ideal object point on the other hand has by Lagrange's theorem the coordinates

$$\mathbf{h}_j = (N_1u_{01}h_1/N_ju_{0j},\ O). \tag{2.51}$$

If we set

$$\mathbf{H} = \mathbf{h} + \boldsymbol{\varepsilon}, \tag{2.6}$$

then the quantity we are chiefly interested in is $\boldsymbol{\varepsilon}_k'$, for this clearly represents the aberrations of the system. Note that

$$\mathbf{H}_1 = (h_1,\ O) \equiv (l_{01}V_1 - Y_1,\ l_{01}W_1 - Z_1). \tag{2.61}$$

3. If ΔX_j denotes the change in a quantity X_j associated with a ray because of refraction at the jth surface, we have at any surface

$$\begin{aligned} \Delta N u_0 \mathbf{H} &= \Delta N u_0 \boldsymbol{\varepsilon} + \Delta N u_0 \mathbf{h}, \text{ by (2.6)} \\ &= \Delta N u_0 \boldsymbol{\varepsilon}, \text{ by Lagrange's theorem. (3.1)} \end{aligned}$$

Denoting $Nu_0\mathbf{H}$ by $\boldsymbol{\Lambda}$ and summing over the k surfaces of the system we have, therefore,

$$N_k'u_{0k}'\boldsymbol{\varepsilon}_k' = N_1u_{01}\boldsymbol{\varepsilon}_1 + \sum_{j=1}^{k} \Delta\boldsymbol{\Lambda}_j$$

since clearly $\boldsymbol{\Lambda}_j' = \boldsymbol{\Lambda}_{j+1}$; also $\boldsymbol{\varepsilon}_1 = 0$, by (2.61), so that

$$\boldsymbol{\varepsilon}_k' = \mu \sum_{j=1}^{k} \Delta\boldsymbol{\Lambda}_j, \tag{3.2}$$

where

$$\mu = 1/N_k'u_{0k}'. \tag{3.21}$$

Accordingly, we now fix our attention on the individual contributions $\Delta\boldsymbol{\Lambda}_j$. Omitting the subscript j

$$\Delta\boldsymbol{\Lambda} = \Delta N u_0(l_0\mathbf{V} - \mathbf{Y}) = \Delta N(y_0\mathbf{V} - u_0\mathbf{Y}). \tag{3.3}$$

Let the normal to the surface at the point of incidence P of the ray intersect the x axis in C, and denote the distance of C from the pole A by r. In the paraxial limit (i.e., as $P \to A$) $r \to r_0$, (*v.* Section 5). Then

$$y_0 = r_0(i_0 + u_0); \quad \Delta y_0 = 0, \tag{3.31}$$

and

$$\Delta N i_0 = 0, \text{ by Snell's law.} \tag{3.32}$$

Therefore,

$$\begin{aligned} \Delta\boldsymbol{\Lambda} &= \Delta N[(i_0 + u_0)(r_0\mathbf{V} - \mathbf{Y}) + i_0\mathbf{Y}] \\ &= (i_0 + u_0)\Delta[N(rV - \mathbf{Y}) + N(r_0 - r)\mathbf{V}] \\ &\qquad + Ni_0\Delta\mathbf{Y}. \end{aligned} \tag{3.4}$$

[3] H. A. Buchdahl, Proc. Phys. Soc. **58**, 551 (1946).

Now the components of the normal $\mathfrak{N}(=\boldsymbol{PC})$ are easily seen to be

$$(x-r,\ y,\ z)\equiv(x-r,\ Y-xV,\ Z-xW),\quad \text{by (2.4)};\qquad (3.41)$$

where x, y, z are the coordinates of P. Also, the unit vector in the direction of the ray, $\mathcal{E}$, has the components

$$(\alpha,\ -\beta,\ -\gamma).\qquad (3.42)$$

If ω is an undetermined factor, the laws of refraction are summed up in the equation

$$\Delta N\mathcal{E}=\omega\mathfrak{N},$$

which on vectorial multiplication by $\mathfrak{N}$ at once yields

$$\mathfrak{N}\times\Delta N\mathcal{E}=0.\qquad (3.43)$$

Substituting the actual components of $\mathfrak{N}$ and $\mathcal{E}$ as given by (3.41) and (3.42) and remembering the definition (2.1) of $\mathbf{V}$, the y and z components of (3.43) give

$$\Delta N\alpha(\mathbf{Y}-r\mathbf{V})=0.\qquad (3.5)$$

The first term in (3.4) now becomes

$$\begin{aligned}(i_0+u_0)\Delta N(r\mathbf{V}-\mathbf{Y})&=(i_0+u_0)\Delta N\alpha(r\mathbf{V}-\mathbf{Y})/\alpha\\&=(i_0+u_0)N(r\mathbf{V}-\mathbf{Y})\alpha\Delta(1/\alpha).\end{aligned}\qquad (3.51)$$

Also, putting $t=x$ in (2.4), it follows at once that

$$\Delta\mathbf{Y}=x\Delta\mathbf{V}.\qquad (3.52)$$

Hence, finally,

$$\begin{aligned}\Delta\mathbf{\Lambda}=N(i_0+u_0)(r\mathbf{V}-\mathbf{Y})(\alpha/\alpha'-1)\\+(r_0-r)(i_0+u_0)\Delta N\mathbf{V}+Ni_0x\Delta\mathbf{V}.\end{aligned}\qquad (3.6)$$

4. Regarding $\mathbf{Y}_1$, $\mathbf{V}_1$, y_{01}, u_{01} for the moment as six independent variables we may think of the right-hand side of (3.6) as expanded in a series of ascending powers of $\mathbf{Y}_1$, $\mathbf{V}_1$. This expansion will consist of a series of homogeneous polynomials of degree 3, 5, 7, $\cdots$. For the terms of even degree must be absent since, on account of the symmetry of the system, a reversal of the signs of $\mathbf{Y}_1$ and $\mathbf{V}_1$ merely reverses the sign of $\Delta\mathbf{\Lambda}$, while the linear terms are absent since in the paraxial limit $\Delta\mathbf{\Lambda}=0$, Λ_y, and Λ_z, each being of the form of a Lagrange invariant. Writing $O(m)$ for any expression not containing terms of degree less than m we have, therefore,

$$\Delta\mathbf{\Lambda}=\Delta N(y_0\mathbf{V}-u_0\mathbf{Y})=O(3).\qquad (4.1)$$

Summing over the first $j-1$ surfaces of the system

$$\begin{aligned}N_j(y_{0j}\mathbf{V}_j-u_{0j}\mathbf{Y}_j)\\=N_1(y_{01}\mathbf{V}_1-u_{01}\mathbf{Y}_1)+O(3).\end{aligned}\qquad (4.2)$$

If we now choose for $(y_{01},\ u_{01})$ the particular pairs of values $(1,0)$ and $(0,1)$ we obtain, respectively, by (2.2)

$$\left.\begin{aligned}N_j(y_{pj}\mathbf{V}_j-u_p\mathbf{Y}_j)&=N_1\mathbf{V}_1+O(3),\\N_j(y_{qj}\mathbf{V}_j-u_{qj}\mathbf{Y}_j)&=-N_1\mathbf{Y}_1+O(3).\end{aligned}\right\}(4.21)$$

This pair of equations may be solved for $\mathbf{Y}_1$, $\mathbf{V}_1$; making use of (2.3)

$$\left.\begin{aligned}\mathbf{Y}_j&=y_{pj}\mathbf{Y}_1+y_{qj}\mathbf{V}_1+O(3),\\\mathbf{V}_j&=u_{pj}\mathbf{Y}_1+u_{qj}\mathbf{V}_1+O(3).\end{aligned}\right\}\qquad (4.3)$$

If as in Section 2 we write small letters for the corresponding capitals to denote quantities associated with a paraxial ray the initial data of which are

$$(y_1,\ u_1)=(Y_1,\ V_1),\qquad (4.31)$$

then we may write

$$Y_j=y_j+O(3),\quad V_j=u_j+O(3).\qquad (4.4)$$

5. Since by hypothesis each refracting surface is a surface of revolution, we may specify its shape by means of an equation of the form

$$x=\theta_1\chi+\theta_2\chi^2+\theta_3\chi^3+\cdots,\qquad (5.1)$$

where the θ_i are constants, and $\chi=y^2+z^2$.

No restriction is placed upon the θ_i except insofar as we naturally demand that the series (5.1) shall converge sufficiently rapidly for practical purposes. Comparing (5.1) with the equation of the sphere

$$(x-r_0)^2+\chi=r_0^2,\qquad (5.11)$$

we see by comparing coefficients that the paraxial properties of the surface (into which the first term of the series (5.1) alone enters) are those of a spherical surface of radius

$$r_0=1/2\theta_1.\qquad (5.12)$$

Considering the section of the surface by the tangential plane it is easily seen that

$$r=x+yy'=x+\tfrac{1}{2}[d(y^2)/dx].$$

More generally, by symmetry,

$$r=x+\tfrac{1}{2}d\chi/dx=x+(2dx/d\chi)^{-1}.\qquad (5.2)$$

Using (5.1) we therefore find

$$r=\theta_1\chi+(2\theta_1+4\theta_2\chi)^{-1}+O(4)$$
$$=\theta_1\chi+(1/2\theta_1)-(\theta_2/\theta_1^2)\chi+O(4).$$

Therefore, by (5.12),

$$r-r_0=-4r_0^2(\theta_2-\theta_1^3)\chi+O(4). \qquad (5.3)$$

Moreover, x is obviously an even function of the coordinates and it vanishes paraxially, so that $x=O(2)$. Hence it follows from (2.4) that

$$\chi=y^2+z^2=Y^2+Z^2+O(4), \qquad (5.4)$$

Therefore,

$$r_0-r=4r_0^2(\theta_2-\theta_1^3)(Y^2+Z^2)+O(4),$$
$$x=(Y^2+Z^2)/2r_0+O(4). \qquad (5.5)$$

6. Substituting (5.5) in the expression (3.6) we now have, if $Ni_0r_0=c_0$,

$$\Delta\mathbf{\Lambda}=\tfrac{1}{2}N(i_0+u_0)(r_0\mathbf{V}-\mathbf{Y})\Delta(Y^2+W^2)$$
$$+\tfrac{1}{2}(c_0/r_0^2)(Y^2+Z^2)\Delta\mathbf{V}$$
$$+4(\theta_2-\theta_1^3)r_0y_0(Y^2+Z^2)\Delta N\mathbf{V}+O(5), \qquad (6.1)$$

since

$$\frac{\alpha}{\alpha'}=\left(\frac{1+V'^2+W'^2}{1+V^2+W^2}\right)^{\frac{1}{2}}=1+\tfrac{1}{2}\Delta(V^2+W^2)+O(4).$$

It will be noticed that (6.1) differs from the corresponding equation which holds for a spherical surface only through the presence of the additional term containing the factor $(\theta_2-\theta_1^3)$. However, we shall derive the final result in its desired form *ab initio*.

As only primary aberrations are required we may, in (6.1), take $\mathbf{Y}$, $\mathbf{V}$ to be everywhere *linearly* related to $\mathbf{Y}_1$, $\mathbf{V}_1$, as given by (4.3); for it is obvious from the form of the right-hand side that any terms thus omitted can contribute only to $O(5)$. Accordingly, we shall henceforth omit all reference to expressions which are $O(5)$, or which only contribute to the latter.

Consider as usual a pencil of rays lying symmetrically about a principal ray; any ray of it is defined by

$$Y_1=(Y_{pr})_1+\rho y_{01}\cos\theta, \quad Z_1=\rho y_{01}\sin\theta, \qquad (6.2)$$

where $(Y_{pr})_1$ = value of Y_1 for the principal ray, and $(y_{01}\rho, \theta)$ are polar coordinates locating the ray with respect to the principal ray. (By means of (2.2) values of ρ may if desired be correlated with the diameter of the diaphragm which limits the pencil to this aperture.) Then, using the notation (4.4) for quantities referring to the *principal* ray, we have for any member of the pencil (6.2)

$$Y=y_pY_1+y_qV_1=y_p(y_1+\rho y_{01}\cos\theta)$$
$$+y_q(y_1+\rho y_{01}\cos\theta+h_1)/l_{01}, \text{ by (2.61)}$$
$$=y+\rho y_0\cos\theta, \text{ by (2.2) and (4.4)} \qquad (6.21)$$

Also, writing λ for the Lagrange invariant $(=N_1u_{01}h_1)$, we have

$$\lambda=N(y_0u-u_0y)=Nr_0(i_0u-u_0i).$$

Therefore,

$$u=(i/i_0)u_0+(\lambda/c_0). \qquad (6.3)$$

Hence, setting

$$i/i_0=q, \quad q+\rho\cos\theta=\beta, \qquad (6.4)$$

we have

$$Y=r_0(i+u)+\rho y_0\cos\theta$$
$$=r_0(qi_0+qu_0+\lambda/c_0)+\rho y_0\cos\theta.$$

Therefore,

$$Y=\beta y_0+r_0\lambda/c_0.$$

In exactly the same way

$$Z=y_0\rho\sin\theta, \quad V=\beta u_0+\lambda/c_0, \quad W=u_0\rho\sin\theta. \qquad (6.5)$$

Therefore,

$$\Delta(V^2+W^2)=\Delta[(\beta^2+\rho^2\sin^2\theta)u_0^2$$
$$+2\lambda\beta u_0/c_0+\lambda^2/c_0^2]$$
$$=(\beta^2+\rho^2\sin^2\theta)\Delta u_0^2+2\lambda\beta\Delta u_0/c_0; \qquad (6.61)$$

$$r_0V-Y=-\beta r_0i_0, \text{ and so on.} \qquad (6.62)$$

Considering the first two terms in $\Delta\Lambda_y$, these contribute

$$-\tfrac{1}{2}N(i_0+u_0)\beta r_0i_0[(\beta^2+\rho^2\sin^2\theta)(u_0'-u_0)(u_0'+u_0)$$
$$+2\lambda\beta(u_0'-u_0)/c_0]+\tfrac{1}{2}(c_0/r_0^2)[(\beta^2+\rho^2\sin\theta)y_0^2$$
$$+2\lambda r_0\beta y_0/c_0+\lambda^2r_0^2/c_0^2]\beta(u_0'-u_0).$$

Rearranging according to powers of λ this gives without difficulty

$$\tfrac{1}{2}c_0(i_0+u_0)(i_0-i_0')\beta(\beta^2+\rho^2\sin\theta)$$
$$\times(-u_0-u_0'+i_0+u_0)+\beta\lambda^2(u_0'-u_0)/c_0,$$

since the second term cancels the fourth. Now

$$(u_0'-u_0)/c_0=(i_0-i_0')/Nr_0i_0=-(1/r_0)\Delta(1/N)$$
$$=-\tilde{\omega}, \text{ say.} \qquad (6.71)$$

Also, writing

$$S_0=\tfrac{1}{2}c_0(i_0+u_0)(i_0-i_0')(i_0'-u_0), \qquad (6.72)$$

the first two terms of $\Delta\Lambda_y$ contribute

$$\beta(\beta^2+\rho^2\sin^2\theta)S_0-\tfrac{1}{2}\beta\bar{\omega}\lambda^2. \tag{6.8}$$

In the last term of $\Delta\Lambda_y$ (*v.* Section 8).

$$\begin{aligned} Y^2+Z^2 &= y^2+2y_0\rho\cos\theta+\rho^2y_0^2, \\ &\quad \text{by (6.21) and (6.5)}, \\ &= (\gamma^2+\rho^2\sin^2\theta)y_0^2, \end{aligned} \tag{6.81}$$

where, by analogy with (6.4),

$$p=y/y_0, \quad \gamma=p+\rho\cos\theta. \tag{6.82}$$

Hence, this term contributes

$$4(\theta_2-\theta_1{}^3)y_0{}^4\gamma(\gamma^2+\rho^2\sin^2\theta)\Delta N, \tag{6.83}$$

since

$$\begin{aligned} r_0\Delta NV &= \Delta NY, \text{ by (6.62)} \\ &= Y\Delta N = y\gamma\Delta N, \text{ by (6.21)}. \end{aligned}$$

Adding (6.8) and (6.83) we have

$$\begin{aligned} \Delta\Lambda_y = \beta(\beta^2+\rho^2\sin^2\theta)S_0 \\ +\gamma(\gamma^2+\rho^2\sin^2\theta)T_0-\tfrac{1}{2}\bar{\omega}\beta\lambda^2, \end{aligned} \tag{6.9}$$

where

$$T_0=4(N'-N)(\theta_2-\theta_1{}^3)y_0{}^4. \tag{6.91}$$

The expression for $\Delta\Lambda_z$ is now easily derived on exactly similar lines, and gives

$$\begin{aligned} \Delta\Lambda_z = \rho\sin\theta[(\beta^2+\rho^2\sin^2\theta)S_0 \\ +(\gamma^2+\rho^2\sin^2\theta)T_0-\tfrac{1}{2}\bar{\omega}\lambda^2]. \end{aligned} \tag{6.10}$$

7. The expressions (6.9) and (6.10) may now be rearranged according to powers of ρ. This task is considerably eased by noting the symmetry which obtains between the terms in S_0 and T_0, respectively. We find

$$\begin{aligned} \Delta\Lambda_y = \rho^3\cos\theta(S_0+T_0)+\rho^2(1+2\cos\theta)(qS_0+pT_0) \\ +\rho\cos\theta(3q^2S_0+3p^2T_0-\tfrac{1}{2}\bar{\omega}\lambda^2) \\ +(q^3S_0+p^3T_0-\tfrac{1}{2}q\bar{\omega}\lambda^2), \end{aligned} \tag{7.1}$$

$$\begin{aligned} \Delta\Lambda_z = \rho^3\sin\theta(S_0+T_0)+2\rho^2\sin\theta\cos\theta(qS_0+pT_0) \\ +\rho\sin\theta(q^2S_0+p^2T_0-\tfrac{1}{2}\bar{\omega}\lambda^2). \end{aligned} \tag{7.1}$$

To obtain the final aberrations in the image space we need only sum over the individual surfaces of the system according to (3.2). It is convenient to introduce the following abbreviations:

$$\begin{aligned} \sigma_1 &= \mu\sum(S_0+T_0), \\ \sigma_2 &= \mu\sum(qS_0+pT_0), \\ \sigma_3 &= \mu\sum(q^2S_0+p^2T_0), \\ \sigma_4 &= \tfrac{1}{2}\mu\lambda^2\sum\bar{\omega}, \\ \sigma_5 &= \mu\sum(q^3S_0+p^3T_0-\tfrac{1}{2}q\bar{\omega}\lambda^2), \end{aligned} \tag{7.2}$$

where the summations are extended over all the surfaces of the system. Then

$$\begin{aligned} \epsilon_{yk}{}' &= \sigma_1\rho^3\cos\theta+\sigma_2\rho_2(2+\cos2\theta) \\ &\quad +(3\sigma_3-\sigma_4)\rho\cos\theta+\sigma_5, \\ \epsilon_{zk}{}' &= \sigma_1\rho^3\sin\theta+\sigma_2\rho^2\sin2\theta+(\sigma_3-\sigma_4)\rho\sin\theta. \end{aligned} \tag{7.3}$$

8. The expressions (7.2) correspond exactly to the well-known Seidel sums, and indeed reduce to these when the surfaces are spherical, since for such surfaces $\theta_2=\theta_1{}^3$, so that T_0 vanishes. This form of the sums is probably the most convenient for actual computation. Two paraxial rays need to be traced, i.e., a ray through the axial point of the object, which determines the quantities distinguished by the subscript 0, and a principal ray which enters into the σ_i only through the p_j and q_j (apart from λ which is the same at all surfaces). We could have removed p_j also by means of the identity

$$p=q+[\lambda/c_0(i_0+u_0)], \tag{8.1}$$

in which case the principal ray would have entered into the σ_i through the q_j alone, as is the case with the Seidel sums. But from a practical point of view there seems to be little reason for doing so.

The Eqs. (7.3) are, of course, formally the same as those which hold for systems in which the surfaces are spherical. Hence the usual discussions concerning the (geometrical) significance of the σ_i in relation to the appearance of the image, etc. hold unchanged.[4] In particular, of course, the vanishing of the five sums (7.2) is a necessary and sufficient condition for the absence of the monochromatic primary aberrations for a given position of the object plane. (Since p_j and q_j are clearly each proportional to h_1, it follows that if the σ_i vanish for one object height they vanish for all object heights.) The actual values of the σ_i now naturally contain additional terms characteristic of the departure of the surface from sphericity. The expression for the transverse measure of the Petzval curvature, $-\sigma_4$, is unchanged, but the relationship between the *contributions* by a surface to the

[4] G. C. Steward, *The Symmetrical Optical System*, Cambridge Tracts No. 25 (Cambridge University Press, Teddington England, 1928), p. 32.

spherical aberration, coma, and astigmatism is no longer simple.

The further considerable simplifications that arise in the derivation above if all the surfaces are taken to be spherical at the outset are immediately apparent; the result is a method which should prove of value from a didactic point of view.

9. The following is a table of the more important symbols used in the text. The numbers in brackets indicate the equation in which the symbol first occurs.

Symbol	Meaning
$\alpha, -\beta, -\gamma$	direction cosines of ray. (2.1)
β	$q+\rho\cos\theta$. (6.4)
c_0	Nr_0i_0. (6.1)
γ	$p+\rho\cos\theta$. (6.82)
Δ	$\Delta X_j=X_j'-X_j$. (3.1)
$\mathfrak{x}$	components of displacement of ray with respect to ideal object point ($=\mathbf{H}-\mathbf{h}$). (2.6)
$\mathbf{H}$	coords. of pt. of intersection of ray with ideal object plane. (2.5)
$\mathbf{h}$	ideal object height. (2.51)
k (suffix)	refers to last surface. (3.2)
θ_l	coefficients determining shape of surface. (5.1)
i	paraxial angle of incidence. (3.31)
l	paraxial intersection length. (2.5)
$\mathbf{\Lambda}$	$Nu_0\mathbf{H}$. (3.1)
λ	Lagrange invariant. (6.3)
μ	$1/N_k'u_{0k}'$. (3.2)
N	refractive index. (2.3)
0 (suffix)	refers to ray through axial point of object. (2.5)
$O(m)$	terms of degree not less than m in the coordinates. (4.1)
p, q (suffixes)	defined by $a_j=a_{pj}y_1+a_{qj}u_1$. (2.2)
p	y/y_0. (6.82)
$\bar{\omega}$	$r_0^{-1}\Delta(N^{-1})$. (6.71)
q	i/i_0. (6.4)
r_0, r	associated with normals to surface at points of incidence. (3.31; 3.4)
ρ, θ	$\rho y_{01}, \theta$ are polar coordinates of a ray with respect to the principal ray in first polar tangent plane. (6.2)
S_0	$\frac{1}{2}c_0(i_0+u_0)(i_0-i_0')(i_0'-u_0)$. (6.72)
σ_i	aberration sums. (7.2)
T_0	$4(N'-N)(\theta_2-\theta_1^3)y_0^4$. (6.9)
u	angle between paraxial ray and axis of system. (2.2)
V, W	direction ratios of ray, $(\beta/\alpha, \gamma/\alpha)$. (2.1)
x	x coordinate of point of incidence of ray. (3.41)
Y, Z	coordinates of point of intersection of ray with polar tangent plane. (2.4)
y	paraxial incidence height. (2.2)
$'$	denotes value of corresponding undashed quantity after refraction. (3.2)

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 1 JANUARY, 1948

Optimum Band Width for Two Layer Anti-Reflection Films

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(Received July 22, 1947)

To determine the reflection from a two layer anti-reflection film on glass the ideas and terminology of network analysis are introduced. Those parts of network theory to be used are briefly reviewed. This theory is shown to provide a clear physical picture of the field changes which occur with varying film parameters. It is shown that there is a relation connecting these parameters which defines an optimum design for best bandwidth. This design yields a reflection curve having two points of zero reflection and in a typical case gives less than 0.005 reflectivity over a range extending well beyond the visible spectrum at both ends. If, because of physical limitations, the optimum proves to be unattainable, then the conditions for closest approach are outlined.

1. INTRODUCTION

IT is often advantageous to use the concept of impedance in analyzing electromagnetic wave problems when the conditions are such that the concept applies. We shall use here the idea of impedance and the methods of network analysis to find the optimum characteristics of a two layer, anti-reflection film on glass. The optimum characteristics are defined as those that yield the widest possible frequency band over which the reflection is less than some specified amount. It is assumed that the indices of refraction of the initial and final media are given, and that they are not functions of frequency.

Network analysis gives a simple physical picture of the current and voltage relationships between the input and output ends of a four terminal network. This picture is built up through the use of the defined quantities, the image impedances and the transfer constant. These, in turn, are defined in terms of the internal network constants. The transfer constant gives information on the loss in energy between input and output, and the image impedances are used to judge the reflection losses at each end. The effects on these parameters of changes in network configuration are readily evaluated and correlated with the transmission characteristics. In this way it is often possible to see quickly what combination of constants is most advantageous in producing a desired overall transmission. We shall see for instance in the present case that two points of zero reflection can be easily obtained within one pass band and that this offers a possibility of greatly improved performance. The remainder of the first section will be devoted to a brief review of those portions of network theory which are to be used.

The precepts of network theory were extended to structures having distributed constants by Mason[1] and later to electromagnetic field problems in general by Schelkunoff.[2] We shall be concerned with plane waves of light whose propagation can be described completely in terms of one dimension. It is to just such waves that the idea of impedance can be adopted. The equations defining the wave motion for these light waves are identical with those for an electrical transmission line if we take as analogous quantities voltage and the magnitude of the electric field vector, and also current and the magnitude of the magnetic field vector. We shall assume henceforth that this parallelism holds and write network equations in terms of the field quantities E and H.

In writing network equations it is necessary to define impedance. The impedance of space is defined as the ratio

$$Z_0 = E/H = (\mu_0/\epsilon_0)^{\frac{1}{2}}, \tag{1}$$

where μ_0 and ϵ_0 are respectively the permeability and dielectric constant of free space in MKS units. The ratio of the impedance of a vacuum to that of some other non-conducting medium is

$$\frac{Z_0}{Z_{01}} = \left(\frac{\mu_0\epsilon_1}{\epsilon_0\mu_1}\right)^{\frac{1}{2}} = \left(\frac{\epsilon_1}{\epsilon_0}\right)^{\frac{1}{2}} = n_1. \tag{2}$$

The permeabilities are assumed equal. In Eq.

[1] W. P. Mason, Bell Sys. Tech. J. 6, 258 (1927).
[2] S. A. Schelkunoff, Bell Sys. Tech. J. 17, 17 (1938).

(2), n_1 is the index of refraction of the substance 1.

A four terminal network is defined here as a section of space bounded by two parallel planes which are normal to the direction of wave propagation. Any changes in the properties of the space must be capable of being completely specified in terms of the dimension normal to the boundary surfaces. The term "four terminal network" is a carry-over from the theory of low frequency electrical networks; for convenience of reference it will be retained even though it has no particular physical significance when applied to the present problem.

It can be shown[3,4] that the fields at the input of a four terminal network are given in terms of the fields at the output by the following matrix equation.

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \times \begin{bmatrix} E_2 \\ H_2 \end{bmatrix}. \tag{3}$$

The input is end 1, the output, end 2. The quantities A, B, C, and D are termed the general circuit constants. For the networks to be considered, the determinant of the square matrix is equal to unity.

$$AD-BC=1. \tag{4}$$

Accordingly there are three independent constants which specify completely the relation between input and output fields. In terms of these three quantities the image parameters are[5]

$$Z_{I1}=(AB/CD)^{\frac{1}{2}}, \tag{5}$$

$$Z_{I2}=(DB/CA)^{\frac{1}{2}}, \tag{6}$$

$$\theta=\alpha+j\beta=\cosh^{-1}(AD)^{\frac{1}{2}}=\sinh^{-1}(BC)^{\frac{1}{2}}, \tag{7}$$

where $j=(-1)^{\frac{1}{2}}$. We can prove that when the load and generator impedances are equal to their respective image impedances,

$$e^{2\theta}=E_1H_1/E_2H_2. \tag{8}$$

The mismatch loss factor of a four terminal network is defined as

$$G^2=|E_2H_2/E_2'H_2'|, \tag{9}$$

where E_2 and H_2 are the field strengths at the output of the given network; and E_2' and H_2' are the fields that would exist at the load if the maximum possible amount of energy were transferred from the input medium to the output. The quantity G is therefore a measure of how good a match is produced by the network since by definition two structures are matched when the maximum amount of power is transferred between them.[6] In terms of the quantities in Eqs. (5), (6), and (7),

$$G^2=\frac{4\eta_1/\eta_2}{|(1+\eta_1/\eta_2)\cosh\theta+(\eta_1+1/\eta_2)\sinh\theta|^2}. \tag{10}$$

In this equation

$$\eta_1=Z_{I1}/Z_g, \quad \eta_2=Z_{I2}/Z_L. \tag{11}$$

Z_g = generator impedance = impedance measured at end 1 of the network looking in the direction from which the energy is arriving but with all sources removed. Z_L = load impedance = impedance measured at end 2 of the network looking in the direction of propagation of the incident energy. The ratios η_1 and η_2 will be called the impedance mismatch factors and are in general functions of frequency. An alternative expression for G is

$$G^2=\frac{4Z_L/Z_g}{|AZ_L/Z_g+D+B/Z_g+CZ_L|^2}. \tag{12}$$

In standard texts on filter theory,[7] it is shown

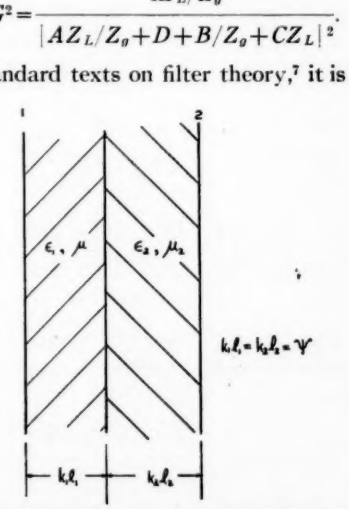

FIG. 1. "Network" composed of two dielectric layers.

[3] E. A. Guillemin, *Communication Networks* (John Wiley and Sons, Inc., New York, 1935), Vol. II.
[4] P. I. Richards, Proc. I.R.E. **34**, 145 (1946).
[5] E. A. Guillemin, *Communication Networks* (John Wiley and Sons, Inc., New York, 1935), Vol. II.
[6] P. I. Richards, Proc. I.R.E. **34**, 145 (1946).
[7] See, for instance, ref. 3 or T. S. Shea, *Transmission Networks and Wave Filters* (D. Van Nostrand Company, New York, 1929).

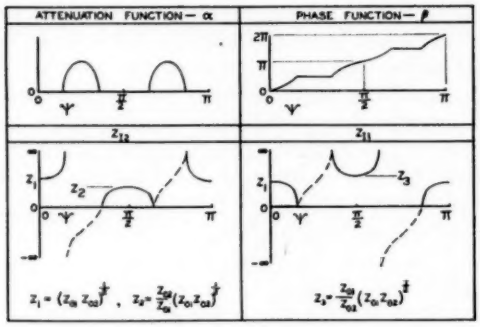

FIG. 2. Image impedances and transfer constant for double layer film.

that the frequency spectrum may be divided into pass bands and stop bands. In the former, θ has no real part and the image impedances are purely resistive; in the latter regions, the opposite conditions prevail and the Z_I's are imaginary and θ has a real part.

Rewriting Eq. (10) to be valid only in the pass bands,

$$G^2=\frac{4\eta_1/\eta_2}{|(1+\eta_1/\eta_2)\cos\beta+j(\eta_1+1/\eta_2)\sin\beta|^2}. \quad (13)$$

From (13) the conditions for complete energy transfer (and hence zero reflection) are easily obtained by putting $G^2=1$. They are solutions of

$$\cos\beta=\frac{\eta_1-1/\eta_2}{[(\eta_1^2-1)(1-1/\eta_2^2)]^{\frac{1}{2}}}. \quad (14)$$

The two solutions of most interest here are:

$$\eta_1=\eta_2=1, \text{ independent of } \beta \quad (15)$$

$$\eta_1=\eta_2, \quad \beta=p\pi. \quad (16)$$

In this equation p must be taken as an integer. Equation (15) states that there is no mismatch at either end of the network and hence, of course, no reflection. Equation (16), on the other hand, requires only that the reflections from each end be equal. Zero over-all reflection is then obtained by making the network phase shift just that to cause the reflection from the input end to cancel that due to the output end. The application of these equations to two layer films will be illustrated in the next section.

2. APPLICATION OF NETWORK THEORY TO TWO LAYER FILMS OF EQUAL ELECTRICAL THICKNESS

Assume that a network is made of two dielectric layers as in Fig. 1. The electrical length of the transmission path in each substance is ψ. Each section of the above network is analogous to a uniform transmission line and has the same matrix. This is,[8]

$$\begin{bmatrix} A_p & B_p \\ C_p & D_p \end{bmatrix}=\begin{bmatrix} \cos\psi & jZ_{0p}\sin\psi \\ j\sin\psi/Z_{0p} & \cos\psi \end{bmatrix}, \quad (17)$$

where $k=2\pi/\lambda_p=2\pi f(\mu_p\epsilon_p)^{\frac{1}{2}}$, f is the frequency, and λ_p is the wave-length in the dielectric. Z_{0p} is the characteristic impedance of the medium and equals $(\mu_p/\epsilon_p)^{\frac{1}{2}}$. It is easy to see that the matrix for the combination of the two layers is just the product of the matrices of the two separate parts.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}=\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}\times\begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}=\begin{bmatrix} \cos^2\psi-(Z_{01}/Z_{02})\sin^2\psi & j(Z_{01}+Z_{02})\sin\psi\cos\psi \\ j(1/Z_{01}+1/Z_{02})\sin\psi\cos\psi & \cos^2\psi-(Z_{02}/Z_{01})\sin^2\psi \end{bmatrix}. \quad (18)$$

From Eq. (18) and Eqs. (5) through (7), the image impedances and transfer constant may be written at once.

$$Z_{I1}=[Z_{01}Z_{02}]^{\frac{1}{2}}\left[\frac{1-(Z_{01}/Z_{02})\tan^2\psi}{1-(Z_{02}/Z_{01})\tan^2\psi}\right]^{\frac{1}{2}},$$

$$Z_{I2}=[Z_{01}Z_{02}]^{\frac{1}{2}}\left[\frac{1-(Z_{02}/Z_{01})\tan^2\psi}{1-(Z_{01}/Z_{02})\tan^2\psi}\right]^{\frac{1}{2}}, \quad (19)$$

$$\cosh\theta=\tfrac{1}{2}[(2-Z_{01}/Z_{02}-Z_{02}/Z_{01})+(2+Z_{01}/Z_{02}+Z_{02}/Z_{01})\cos^2 2\psi]^{\frac{1}{2}}.$$

These functions are shown graphically in Fig. 2 for the assumed condition that $Z_{01}>Z_{02}$. The pass bands are centered at $\psi=p\pi/2$, the stop bands at $\psi=(2p-1)\pi/4$. It will be noticed from the curves that both or either of the two conditions of Eqs. (15) and (16) can be met. The phase shift β is equal to $p\pi$ at the pass band centers, and so by Eq. (16), if η_1 is put equal to η_2 at these points, there will be no reflection. At

[8] P. I. Richards, Proc. I.R.E. **34**, 145 (1946).

the pass band center located at $\psi=\pi/2$,

$$\eta_1=Z_{01}(Z_{01}Z_{02})^{\frac{1}{2}}/Z_{02}Z_g, \tag{20}$$

$$\eta_2=Z_{02}(Z_{01}Z_{02})^{\frac{1}{2}}/Z_{01}Z_L. \tag{21}$$

Putting these equal to one another we obtain

$$Z_{01}^2/Z_{02}^2=Z_g/Z_L. \tag{22}$$

In terms of the indices of refraction this may be written

$$n_2^2/n_1^2=n_L. \tag{23}$$

Here the generator impedance Z_g is assumed to be that of free space for which, of course, $n=1$. Eq. (23) is the same as that given by Mooney[9] for two layer quarter wave films.

Another method of obtaining zero reflection is defined by Eq. (15). This requires that

$$Z_{I1}/Z_g=1, \tag{24}$$

$$Z_{I2}/Z_L=1, \tag{25}$$

at some frequency. Substituting from (19) and recognizing that (24) and (25) must both be true for the same line angle ψ, one obtains

$$\tan^2\psi=\frac{Z_g^2-Z_{01}Z_{02}}{Z_g^2Z_{02}/Z_{01}-Z_{01}^2}=\frac{Z_L^2-Z_{01}Z_{02}}{Z_L^2Z_{01}/Z_{02}-Z_{02}^2}. \tag{26}$$

Writing in terms of the indices of refraction and simplifying, the right hand equality of Eq. (26) may be reduced to

$$n_1n_2=n_L. \tag{27}$$

The left equality yields

$$\tan^2\psi=\frac{n_1n_2-1}{n_1^2-n_2/n_1}. \tag{28}$$

From this equation it is evident that there are two frequencies for which the conditions (24) and (25) are met. This is also apparent in Fig. 3 where the image impedances have been redrawn for the region near $\psi=\pi/2$. The horizontal lines represent the constant generator and load impedances. The levels have been adjusted to make the intersections of Z_{I1} and Z_g occur at the same frequencies as those of Z_{I2} and Z_L as specified in deriving Eq. (26). A qualitative idea of the reflection as a function of ψ may be gained from this figure. The reflection at ψ_1 and ψ_2 will

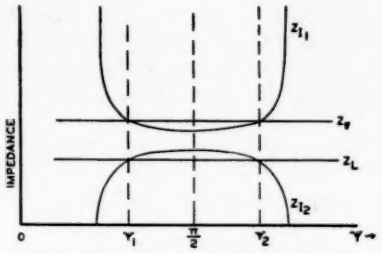

FIG. 3. Image and load impedances.

be zero. At ψ equals $\pi/2$ the mismatch loss factor is

$$G_0=\frac{2(\eta_{10}/\eta_{20})^{\frac{1}{2}}}{1+\eta_{10}/\eta_{20}}. \tag{29}$$

The additional subscript zero has been added to identify this equation as being valid only for the band center. Calculating η_{10} and η_{20}:

$$\eta_{10}=n_2/n_1n_L^{\frac{1}{2}}, \tag{30}$$

$$\eta_{20}=n_1n_L^{\frac{1}{2}}/n_2=1/\eta_{10}. \tag{31}$$

These may be substituted in (29) to find the band center mismatch loss. With the mismatch loss factor known at three points, it is possible to draw a qualitative curve of reflection *vs.* ψ. Since the network is lossless, the reflection coefficient R is related to G by

$$R^2=1-G^2. \tag{32}$$

The reflection coefficient is equal to the square root of the reflectivity as customarily defined in optics. Reflection *vs.* ψ is shown in Fig. 4 for the region near the pass band center. The two points of zero reflection are shown as well as the peak between them. The behavior of R beyond ψ_1 and ψ_2 will be discussed later.

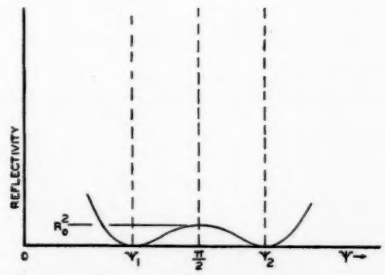

FIG. 4. Reflectivity *vs.* ψ.

[9] R. L. Mooney, J. Opt. Soc. Am. **35**, 574 (1945).

In designing a double layer film R_0^2, the maximum permissible reflectivity at the band center would very likely be given. One could then solve for the values of n_1 and n_2 to give

$$n_1 = n_L^{\frac{1}{2}}[(1+R_0)/(1-R_0)]^{\frac{1}{2}}, \quad (33)$$

$$n_2 = n_L^{\frac{1}{2}}[(1-R_0)/(1+R_0)]^{\frac{1}{2}}. \quad (34)$$

The height of the bump in the center of the reflection curve and the positions of ψ_1 and ψ_2 can be varied by adjusting the heights of the image impedance curves of Fig. 3 relative to Z_g and Z_L. This is done by varying n_1 and n_2. If Z_{I1} and Z_{I2} are brought closer together at the center (while still keeping Eq. (27) satisfied in order that $\eta_1 = \eta_2 = 1$ at $\psi = \psi_1$ or ψ_2) then R_0 must increase and ψ_1 and ψ_2 will diverge from $\pi/2$. Conversely, if Z_{I1} and Z_{I2} are made to recede from one another, R_0 will decrease continually, and ψ_1 and ψ_2 will approach together until they coincide at $\psi = \pi/2$. At this point $R_0 = 0$ and Eqs. (15) and (16) are both satisfied. If Z_{I1} and Z_{I2} are made to move still further apart, the image impedances will not be matched anywhere; Eq. (15) can no longer be satisfied under these conditions and the only hope of zero reflection is to satisfy (16).

It will now be proved that the conditions represented by Fig. 4 and Eqs. (33) and (34) represent the optimum design for best bandwidth as defined earlier. We will use the inverse of the mismatch loss factor as given by (12); this is written below.

$$1/G^2 = \frac{Z_g}{4Z_L}\left|A\frac{Z_L}{Z_g} + D + \frac{B}{Z_g} + CZ_L\right|^2. \quad (35)$$

Expanding and writing in terms of the indices of refraction,

$$1/G^2 = \left(\frac{n_L}{16}\right)\left|\left[\frac{1}{n_L}\left(1-\frac{n_2}{n_1}\right) - \frac{n_1}{n_2} + 1\right] + \left[\frac{1}{n_L}\left(1+\frac{n_2}{n_1}\right) + \frac{n_1}{n_2} + 1\right]\cos\rho + 2j\left[\frac{1}{n_1} + \frac{1}{n_2}\right]\sin\rho\right|^2. \quad (36)$$

In (36), $\rho = 2\psi$. This equation is of the general form

$$1/G^2 = a_0' + a_1\cos\rho + a_2\cos 2\rho + b_1\sin\rho + b_2\sin 2\rho, \quad (37)$$

where the a's and b's are constant functions of n_1 and n_2. The function $1/G^2$ is periodic with a fundamental period in ρ of 2π, and has terms representing a constant component, a fundamental and a second harmonic only. The order of the highest harmonic is a function of the number of cascaded sections only and not of the indices of refraction and is therefore fixed for all two layer quarter wave films. As a consequence, $1/G^2$ has at most four maxima and minima in a fundamental period (see Appendix). Also, the minimum value of $1/G^2$ is unity because a value less than this would imply that more energy was received at the output than was incident at the input. Equation (37) can be modified to read

$$1/G^2 = 1 + a_0 + a_1\cos\rho + a_2\cos 2\rho + b_1\sin\rho + b_2\sin 2\rho = 1 + J, \quad (38)$$

where J has a minimum value of zero. J is related to the reflectivity by

$$J = \frac{R^2}{1-R^2}. \quad (39)$$

A curve representing the conditions of Fig. 4 but plotted in terms of J and expanded to show a full cycle is given in Fig. 5 as the solid curve. The band width for a given maximum mismatch (or

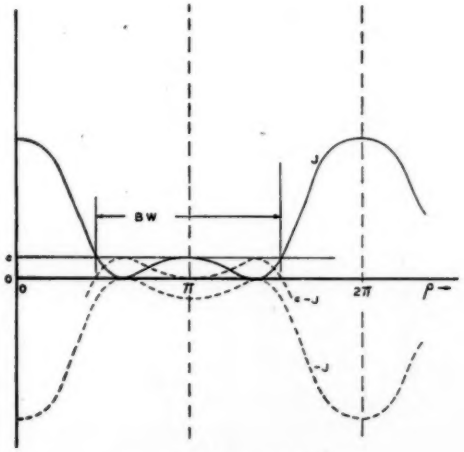

FIG. 5. J and limits of J vs. ρ.

reflection) loss is indicated by BW, and the maximum allowable value of J within the range BW is denoted by c. Suppose that there is some other function (obtained by modifying n_1 and n_2) which gives the same maximum loss but a wider band for a given value of n_L. The new function must be of the form implied by (38) for J. Represent it by

$$\bar{J}=J+K. \tag{40}$$

$\bar{J}$ must contain no function of a higher multiple of ρ than 2 and hence neither may K. To show the same maximum loss, the function $\bar{J}$ can never go above c within the limits of BW so that $K \leqslant c-J$ in this region. This limit is indicated by a dotted curve in Fig. 5. Also, since $\bar{J}$ must always be greater than zero, $K \geqslant -J$; this limit, too, is shown on Fig. 5. Now examine J at $\rho=2q\pi$ where q is an integer. From (36)

$$1/G^2=n_L(1/n_L+1)^2/4 \tag{41}$$

and is entirely independent of n_1 and n_2. As a result,

$$\bar{J}=J, \quad (\rho=2q\pi) \tag{42}$$

because the two functions $\bar{J}$ and J differ only in n_1 and n_2 at any frequency. This requires that $K=0$ at these points. Now, by examining Fig. 5 one can see that K must be a function having at least 6 maxima and minima per cycle or else must be identically zero. Because the highest multiple of ρ occurring in K is 2, K may have at most 4 maxima and minima per cycle. K must, consequently, be zero everywhere; and there is no function yielding a wider band for the given maximum loss than does J.

A calculated curve of a typical case is shown in Fig. 6. The glass base was assumed to have an index of refraction n_L of 1.517. For a maximum mid-band reflectivity of 0.005 the values of n_1 and n_2 were, respectively, 1.151 and 1.318. From available information, the first of these is below the values easily obtainable at the present time. It is interesting to note though that if this low index were possible, a two-layer film could be put on the glass which would reduce the reflection to 0.005 or less between limits which extend well beyond the visible spectrum at both ends. This is indicated in Fig. 6 where a scale in Angstrom units is shown with the band center arbitrarily put as 5600A. The limits for this case are 3730A and 11,200A. These limits are only accurate for constant indices of refraction. Since these quantities vary with frequency, the curve of reflectivity must be modified to take this into account. The band limits will change somewhat and the curve will become assymmetric.

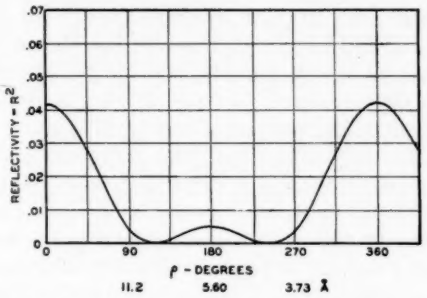

FIG. 6. Calculated reflectivity *vs.* ρ for a maximum pass band reflectivity of 0.005. $n_1=1.151$, $n_2=1.318$, $n_L=1.517$. (Wave-length scale should read in units of $A\times10^3$.)

It is plain from an examination of the image parameters (19) and of the mismatch loss factor that, for zero reflection at at least one point, the form of J passes continually from that of Fig. 6, noted ① on Fig. 7, to that of ② and then to ③ on Fig. 7. Eq. (27) is satisfied for ① and Eq. (23) for ③. Curve ② will be produced when both (27) and (23) are satisfied, or, under some conditions when (23) alone is fulfilled. Furthermore, in going from ① to ② to ③, the quantities n_1 and n_2 must both increase in magnitude for a constant value of n_L. From these considerations one can say that for best bandwidth the lowest possible values of n_1 and n_2 should be chosen. It is also possible to say that, unless the indices of both films are below n_L, the bandwidth will be less than that of a single quarter wave film.

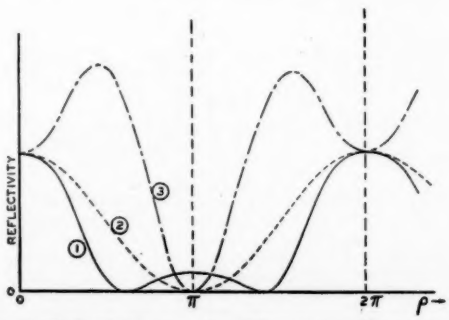

FIG. 7. Reflectivity *vs.* ρ for different matching criteria.

The same general principles apply for non-normal incidence. Schelkunoff[10] has shown that waves obliquely incident upon a plane surface can be considered to have a wave impedance normal to the surface given by $Z_0 \cos\phi$ or by $Z_0 \sec\phi$ depending upon the polarization. The first case is for the E vector in a plane perpendicular to the surface and the second for the H vector in this plane. The angle ϕ is measured from a normal to the surface to the direction of wave propagation. A wave of any other polarization must be broken down into the two above. Evidently a design can be optimized only for one of the two defined polarizations. This means that such films as described here tend to produce partial polarization of an obliquely incident light wave containing all polarizations. This has also been demonstrated by Vasicek.[11]

3. CONCLUSION

The methods of network analysis have been used to analyze wave propagation through a two layer anti-reflection film. From this analysis it has been shown that there is an optimum design for best bandwidth, and the characteristics and design equations for this optimum have been given. If the optimum is unattainable, then conditions for closest approach have been outlined.

APPENDIX

To find the maximum possible number of maxima and minima in a fundamental period of

$$f(\theta)=\sum_0^m a_k \cos k\theta+\sum_1^m b_k \sin k\theta, \tag{1a}$$

write it as

$$f(\theta)=\sum_0^m c_k \cos(k\theta+\phi_k), \tag{2a}$$

and differentiate with respect to θ.

$$f'(\theta)=-\sum_1^m kc_k \sin(k\theta+\phi_k). \tag{3a}$$

This is the imaginary part of

$$f'(\theta)=I_m\left(-\sum_1^m kc_k Z_k Z^k\right), \tag{4a}$$

where

$$Z=e^{j\theta}, \quad Z_k=e^{j\phi_k}.$$

$I_m(\ )$ means that the imaginary part only is to be taken.

Equation (4a) represents $f'(\theta)$ as the imaginary part of a polynomial in Z. This polynomial may be factored in terms of its roots r_k.

$$f'(\theta)=I_m\left(\prod_1^m (Z-r_k)\right)=I_m(Me^{j\Omega}). \tag{5a}$$

The variable Z has a magnitude of unity and in the complex plane lies always on the unit circle; it makes one complete circuit of that circle for a change in θ of 2π which is the fundamental period of $f(\theta)$. The product (5a) can be considered as the product of all the vectors from the point Z to the roots r_k. If all of the roots r_k are within the unit circle, then, as Z traverses the circle once, each vector in the product (5a) contributes a change of 2π to Ω. The angle Ω changes by $2m\pi$, there are $2m$ chances for the imaginary part of $f'(\theta)$ to go through zero, and there can be $2m$ maxima and minima of $f(\theta)$. If some of the roots are on the unit circle and the rest are inside, the ones on the circle contribute a change of π in Ω. However, a root on the unit circle will produce a zero of M for one value of θ and each root still contributes $2m$ zeros to $f'(\theta)$. Roots outside the unit circle contribute less than π variation to Ω, and there is a possibility of fewer than $2m$ zeros in $f'(\theta)$. The maximum possible number of maxima and minima is then $2m$ as, of course, one would intuitively expect.

[10] S. A. Schelkunoff, *Electromagnetic Waves* (D. Van Nostrand Company, New York, 1943), pp. 251–254.
[11] A. Vasicek, J. Opt. Soc. Am. **37**, 145 (1947).

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 1 JANUARY, 1948

The Effect of Light-Absorption on the Shape of the Photographic H. and D. Curve*

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(Received July 24, 1947)

A theoretical treatment is first given to show how the gamma-value of the photographic H. and D. curve varies with the light absorption in an emulsion. The treatment is based on the idea that an emulsion can be subdivided into a number of layers and that the total H. and D. curve of the entire emulsion can be obtained by summation of the elementary H. and D. curves for the separate layers. The absorption of the emulsion is expressed in terms of the ratio, $\log I_T/I_B$, where I_T and I_B represent the intensities of photographically active light in the top and bottom layers, respectively, of the emulsion. Theoretical curves giving $\gamma/D_{\max}$ as a function of the ratio, $\log I_T/I_B$, are given for several widely different types of blue-sensitive emulsions. The curves are compared with experimental measurements carried out by varying the wave-length of the exposing light. The experimental results are found to be in fair agreement with the theoretical curves.

The quantity, $\log I_T/I_B$, can be varied also by varying the emulsion thickness, keeping the absorption coefficient of the emulsion constant. Under these conditions, this theory gives curves for the variation of $\gamma/D_{\max}$ as a function of emulsion thickness. The curves are accordingly tested, using different layer thicknesses of emulsion, and the results are again found to be in agreement with the theoretical curves.

Finally, it is shown, by assuming that the maximum density of an emulsion varies linearly with emulsion thickness, that curves predicting gamma as a function of emulsion thickness can be obtained. Curves of this type are derived and tested by experiment.

IT is well known that the absorption of the exposing light on passage through the photographic emulsion affects the shape of the characteristic curve. This is readily verified by impressing two graded exposures on a non-sensitized emulsion using two different wave-length radiations, e.g., blue-green light and ultraviolet light, and noting the difference in slope of the characteristic curves obtained. In the case of the blue-green light, which is only slightly absorbed, the resulting curve is steeper than the curve obtained with the ultraviolet exposure. With the more highly absorbed light, the upper layers of the emulsion shield the lower layers. Consequently, a greater incident exposure is required to bring up to a developable state the grains lying near the bottom of the emulsion. This results in the characteristic curve being spread out along the exposure axis, and therefore in a lower gamma-value. The term "gamma" here refers to the slope of the straight-line part of the characteristic curve.

The purpose of the present paper is to give the results of a theoretical and experimental study of the variation of gamma with absorption, and to show how this factor is related to emulsion thickness and maximum density.

THEORETICAL ANALYSIS

The method of procedure will be first to analyze the problem of gamma *versus* absorption from a theoretical point of view, and in this way derive curves showing how the gamma of an emulsion should vary with absorption in view of certain obvious physical factors involved.[1] The second step consists in comparing these theoretical curves with experimental data in order to ascertain the extent to which they represent the true behavior of gamma with absorption for actual emulsions.

For purposes of the analysis, the photographic emulsion will be assumed to be made up of a

* Communication No. 1152 from the Kodak Research Laboratories.

[1] L. Silberstein has given a theoretical treatment of the problem of the change in slope of the H. and D. curve with change of absorption of the emulsion (J. Opt. Soc. Am. **32**, 326, 1942). In this paper he gives a beautifully simple formula for deriving the point-by-point slope, $g(E)$, of the actual H. and D. curve for an emulsion of transmission, T, from the density values of the ideal (absorptionless) H. and D. curve at the exposure values, E. This formula is

$$g(E)=f(E)-f(TE)/\log T,$$

and can be proved to hold rigorously, regardless of the nature of the density law,

$$D=f(E),$$

for the emulsion in question. The gamma-transmission curves in the present paper were derived by the author before he was aware of Silberstein's formula, but the theoretical analysis could as well have been carried out by the Silberstein formula and with less work. However, the more crude graphical method used here may serve to make the analysis somewhat clearer to the reader.

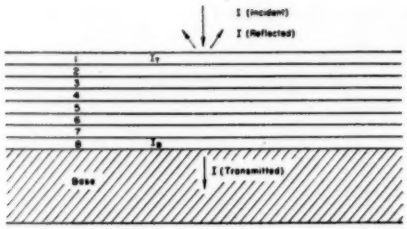

FIG. 1. Diagram showing emulsion divided into a number of hypothetical layers.

number of identical thin layers, as shown in Fig. 1. The number of layers into which the emulsion is thus subdivided is purely arbitrary, provided that the number of layers is above a certain minimum required to give smoothness in the results to follow. Preliminary work showed that division into eight layers was sufficient for this purpose, and this number was accordingly used. The characteristic density-log exposure curve (hereafter called the H. and D. curve) of the complete emulsion layer is likewise supposed to be made up by addition of the elementary H. and D. curves of the separate layers. In order to determine the shape of the H. and D. curve for one of the single elementary layers, the hypothetical case of an emulsion of zero light-absorbing power is considered. In this case, the composite H. and D. curve of the entire emulsion would result from the direct superposition of the eight elementary H. and D. curves of the separate layers. Thus, the H. and D. curve of an elementary layer may be obtained simply by dividing the ordinates of this special H. and D. curve by the number of layers, in the present case, eight. This is illustrated in (A) of Fig. 2. Conversely, the composite H. and D. curve (a) may be considered as made up by the direct superposition of the eight elementary H. and D. curves.

All curves of Fig. 2 are plotted in the form $D/D_{\max}$ *versus* log exposure instead of the usual way of D *versus* log exposure. This was done in order to make the analysis generally applicable to all types of emulsions, regardless of their $D_{\max}$ value. The slope of this type of curve is designated by the quantity, $\gamma/D_{\max}$. In this way, gamma is retained for representing the slope of the density-log exposure curve, as is customary. To distinguish between gamma and $\gamma/D_{\max}$, the latter will be referred to as the "reduced gamma". Only intensity-scale H. and D. curves are dealt with in order to avoid complications arising from reciprocity-law failure. With intensity-scale curves, the intensity factor of exposure is varied and the time factor held constant. Consequently, the exposure conditions experienced by the successive layers of the emulsion pass through identical stages, as the exposure is increased, and the H. and D. curves for the elementary layers have the same slopes. This would not be true for time-scale curves.

The effect of absorption on the slope of the H. and D. curve may be seen from Fig. 2(B). In line with the fact that the lower lying layers of the emulsion receive lower intensity light, the eight elementary H. and D. curves are shown spread out along the log exposure axis. The total spread from curves 1 to 8 corresponds to the quantity, $\log I_T/I_B$, where I_T and I_B represent the effective intensities of the exposing light in the top and bottom layers, respectively, of the emulsion (Fig. 1). The method by which the ratio, I_T/I_B, is determined experimentally will be outlined later.

As seen in Fig. 2(B), the characteristic curve (a), is transformed into the characteristic curve, (b), if the absorption factor, $\log I_T/I_B$, increases from 0 to 0.6. Expressed numerically, the $\gamma/D_{\max}$ value is lowered from 1.50 to 1.18. In Fig. 2(C), the absorption factor, $\log I_T/I_B$, is increased to the value 1.20. The corresponding total drop in the $\gamma/D_{\max}$ value is 1.50 to 0.72. In Fig. 2(D), the $\log I_T/I_B$ value is increased to 1.80 and the change in $\gamma/D_{\max}$ is from 1.50 to 0.49. In this series of curves, the starting $\gamma/D_{\max}$ value for zero absorption was arbitrarily set at $\gamma/D_{\max}=1.50$. If a different initial $\gamma/D_{\max}$ (e.g., 1.25 or 1.00, etc.) is assumed, the same changes in the absorption factor, $\log I_T/I_B$, as used above, lead to different changes of $\gamma/D_{\max}$ with absorption for each different initial value.

Proceeding as in Fig. 2, the change of $\gamma/D_{\max}$ with absorption for any initial value can be determined. The complete curves of $\gamma/D_{\max}$ change with absorption (always expressed as a function of $\log I_T/I_B$), for various initial $\gamma/D_{\max}$ values, are shown in Fig. 3. It may be seen that the lower the initial $\gamma/D_{\max}$ value, the less this factor is affected by absorption. For example, an emulsion

which has a γ/D_{max} value of 1.50 for zero absorption is found to have a γ/D_{max} value of 0.30 when the $\log I_T/I_B$ ratio is changed to 3.0. On the other hand, an emulsion having the γ/D_{max} value 0.25 at zero absorption shows practically no change of γ/D_{max} when $\log I_T/I_B$ is increased to 3.0. The dashed curve in Fig. 3 is the upper limiting curve of γ/D_{max} that it is possible to attain with any emulsion. It is the curve of γ/D_{max} for an emulsion having initially an infinite γ/D_{max} value. For this case, the elementary H. and D. curves of the separate layers would be vertical lines, as shown in Fig. 4. From this diagram, it is clear that if these infinitely steep elementary H. and D. curves are spread out along the log exposure axis** in accordance with the factor, $\log I_T/I_B$, and added together to give the new H. and D. curve, the value of γ/D_{max} for this curve will be given by the relation

$$(\gamma/D_{max})_{max} = 1/(\log I_T/I_B).$$

This is the relation plotted as the dashed curve in Fig. 3.

EXPERIMENTAL WORK

In order to test the accuracy of the theoretical diagram of Fig. 3, measurements of γ/D_{max} as a function of $\log I_T/I_B$ were carried out for several emulsions. Independent variation of the ratio, I_T/I_B, was obtained by varying the wave-length of the exposing radiation. For these tests, only blue-sensitive emulsions covering a wide variation of gamma were chosen. The approximate γ, D_{max}, and γ/D_{max} values as determined for λ4800A radiation are given in Table I.

In all cases development was carried out in Kodak D-19b Developer at 65°F. The times of development of the individual tests are given on the figures. The theoretical curves should apply for any type of development provided that development is fairly uniform through the emulsion. In all cases here, it was endeavored to carry development to a point to meet this requirement.

In Fig. 5, the results of measurements of γ/D_{max} for these emulsions are plotted as a function of the quantity, $\log I_T/I_B$. The data describing the experimental points for type of emulsion, wave-length of exposing radiation, and exposure time, are given in Fig. 5. In making the exposures in these experiments, two layers of film or plate were used and the emulsions were placed in contact with each other, as shown in Fig. 6. The exposing light was incident on the base side of the first emulsion, and the light transmitted by this first emulsion was the exposing light for the second emulsion. An intensity-scale exposure impressed on the two emulsions in this way gives an H. and D. curve on each. If these curves are plotted to the same exposure scale, the separation of the two curves along the log exposure axis gives the quantity, $\log I_T/I_B$. It was first thought that this should be done by making exposures through six or eight layers of the emulsion and determining from the resulting densities on the separate layers how the light diminishes in passing through a great thickness of the emulsion. It was found, however, that the quantity, $\log I_T/I_B$, varied linearly with the number of films exposed in this way (see Fig. 9), and therefore an exposure through two layers of emulsion was sufficient to determine the $\log I_T/I_B$ value for a single layer.

In making determinations of the quantity, $\log I_T/I_B$, in this way, it was found desirable to use between the emulsions a thin layer of liquid with refractive index about the same as that of gelatin, in order to eliminate interfacial and internal reflections at the gelatin-air surfaces. The error from the internal reflection of light incident on the back surface of the front film was especially bad in the determination of $\log I_T/I_B$. This is because the light reflected from the rear surface of the first emulsion is not only lost to the second emulsion but is added to the exposure of the first emulsion. The result is a much enhanced value of $\log I_T/I_B$. To eliminate errors from this cause, glycerin or carbon tetrachloride was used between the emulsions. Either of these

TABLE I.

No.	Emulsion type	γ	D_{max}	γ/D_{max}
I	Very fine grain, low speed	3.75	4.0	0.94
II	Fine grain, low speed	2.20	3.9	.56
III	Medium grain, medium speed	1.65	4.5	.37
IV	Large grain, high speed	1.25	4.0	.31

** In order to get smooth results in this case, it would be necessary to increase the number of elementary layers to a very large number.

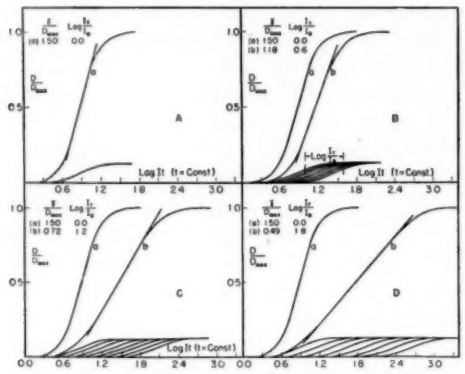

FIG. 2. Diagram to illustrate method of obtaining shape of actual H. and D. curve from ideal absorptionless H. and D. curve.

liquids has an index of refraction sufficiently close to that of gelatin to prevent trouble from this source.

The experimental points in Fig. 5 may be seen to have the same general trend as the theoretical curves. The points for emulsion I, exposed to wave-lengths 4800, 4600, . . . 3600A, lie nearest the curve whose initial γ/D_{max} value is unity. The exposures in this case were 15 seconds. The two points for this same emulsion, obtained with exposures to wave-lengths 4360 and 3124A, were of longer duration (15 minutes), which accounts for the fact that they fall along a higher contrast curve.*** The points for emulsion II follow a course between the two curves starting at $\gamma/D_{max}=0.75$ and $\gamma/D_{max}=0.50$. The points for the low contrast emulsions, III and IV, lie in practically a horizontal line in accord with the theoretical curves for emulsions of these low initial γ/D_{max} values. The slight falling down of these points toward the left of the diagram is probably to be attributed to the long wave-length (non-actinic) radiation employed to reach these low absorption coefficients. The ideal way of carrying out this experiment would be to hold the wave-length of the exposing radiation constant and vary the absorption of the emulsion by impregnating the emulsion with an inert dye. When, as done here, the wave-length of the exposing radiation is varied to obtain different absorptions, there is the possibility that a selective effect is introduced which may affect either the larger or smaller grains to a greater extent. Such an effect would alter the γ/D_{max} value independently of the absorption. It is believed that the falling off of the points of emulsions III and IV toward the left of the diagram is due to this cause. The two points indicated by the diagonal crosses and pertaining to the eight layers of emulsion I were obtained by means of a composite emulsion built up of eight superposed films. The pile of films was exposed as a single emulsion. After development, the densities of the eight films were read separately and added together to give the composite

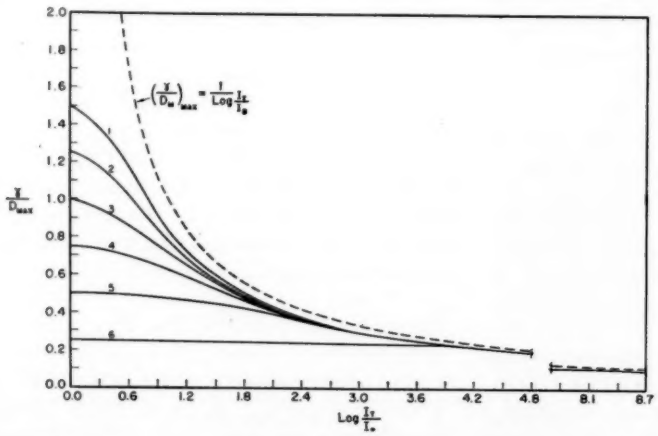

FIG. 3. Plot of γ/D_{max} values as a function of the $\log I_T/I_B$ values obtained by theoretical analysis.

*** On account of the reciprocity-law failure, intensity-scale curves change in gamma-value as the time is changed. Therefore, in comparing experimental points with any particular theoretical curve, the time of all the intensity-scale curves must be held the same.

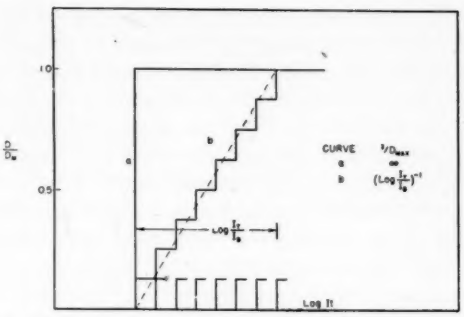

FIG. 4. Change of γ/D_{max} value with $\log I_T/I_B$ for an emulsion with infinitely steep H. and D. curve.

H. and D. curve for the built-up emulsion. By exposing to λ4800 and λ4200A radiations in this manner, γ/D_{max} values for positions far out on the $\log I_T/I_B$ axis were obtained. The points are seen to fall quite well in line with the theoretical curve in this region.

Several interesting points may be noted from the curves of Fig. 5. For values of the absorption ratio, $\log I_T/I_B$, greater than 2.0, the γ/D_{max} value of the ordinary emulsion is determined almost entirely by the absorption of light by the emulsion, and only to a slight extent by the inherent sensitivity distribution among the grains. Change of γ/D_{max} with absorption is large for emulsions having an initially high γ/D_{max} value and is small for those having an initially low γ/D_{max} value. In fact, with emulsions like III and IV, the γ/D_{max} value is affected only very slightly for large changes in absorption. Accordingly, it may be said that the shapes of the H. and D. curves for emulsions of the types, III and IV, are characteristic of the inherent sensitivity distribution among the grains of the emulsion.

CHANGE OF CONTRAST WITH EMULSION THICKNESS

In Figs. 3 and 5, the values of γ/D_{max} are plotted as a function of the quantity, $\log I_T/I_B$, where I_T and I_B are the intensities of light at the top and bottom surfaces, respectively, of the emulsion. Up to this point, in both the theoretical and experimental work, the ratio, I_T/I_B, has been assumed to be varied by changing the absorption coefficient of the emulsion, the emulsion thickness remaining constant. As will be readily appreciated, the factor, $\log I_T/I_B$, can also be varied by changing the thickness of the emul-

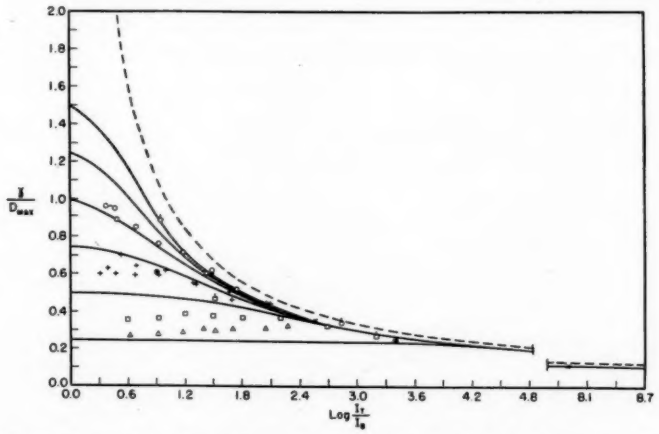

FIG. 5. Comparison of experimental and theoretical γ/D_{max} values over a wide range of $\log I_T/I_B$ values for several emulsions.

Symbol	Emulsion	Wave-lengths, A	Exposure time	Development time (minutes)
○	I	4800 → 3600	15 sec.	6
◇	I	4800 and 4200	15 sec.	4
◇	I	4360 and 3124	15 min.	4
×	I	4800 and 4200 (8 layers)	15 sec.	4
+	II	4800 → 3600	15 sec.	5
⊕	II	4360 and 3124	15 min.	4
□	III	4800 → 3600	15 sec.	6
□	III	4360 and 3124	15 min.	6
△	IV	4800 → 3600	15 sec.	8

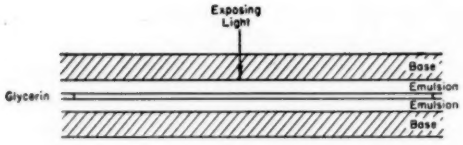

FIG. 6. Illustrating method of measuring $\log I_T/I_B$ values for an emulsion without interreflection of light.

sion, the absorption coefficient being held constant. The theoretical curves of Figs. 3 and 5 are valid for this case as well as for that in which the absorption coefficient is varied. The only requirement is a determination of the way in which $\log I_T/I_B$ varies with emulsion thickness. It will be shown later (see Fig. 9) that the quantity, $\log I_T/I_B$, is a linear function of emulsion thickness. Accordingly, the curves of Figs. 3 and 5 may be considered as portraying also the variation of $\gamma/D_{\max}$ as a function of emulsion thickness. This is indicated on the abscissa of Fig. 7, where the theoretical curves of Fig. 3 are reproduced. The curves are plotted again as a function of $\log I_T/I_B$ but the abscissa scale is put in terms of thickness by means of the relation,

$$\log I_T/I_B = K_1(\text{thickness}).$$

In Fig. 7, experimentally determined values of $\gamma/D_{\max}$ obtained by variation of emulsion thickness are plotted along with the theoretical curves. Emulsions of varying thickness were obtained by piling up films in stacks of two, four, and eight layers. Each stack of film was exposed as though it were a single emulsion. Data are given on the graph to identify the experimental points as to type of emulsion, wave-length of exposing radiation, and number of emulsion layers. The manner in which the quantity, $\log I_T/I_B$, was measured and the $\gamma/D_{\max}$ values obtained for the stacks of film may be seen in Figs. 8–10. In Fig. 8, density-log exposure curves are plotted for eight film layers exposed simultaneously to radiation of wave-length 4800A. To obtain the $\log I_T/I_B$ values for the different thicknesses of emulsion used, the spacing between the curves of Fig. 8 along the log exposure axis was measured. The separation of the first two curves gives the $\log I_T/I_B$ value for one film thickness, the separation between the first and third curves gives the $\log I_T/I_B$ value for two layers, and so forth. The values of $\log I_T/I_B$ thus obtained are shown plotted as a function of emulsion thickness in Fig. 9. These curves show, as stated previously, that the quantity, $\log I_T/I_B$, varies linearly with emulsion thickness.

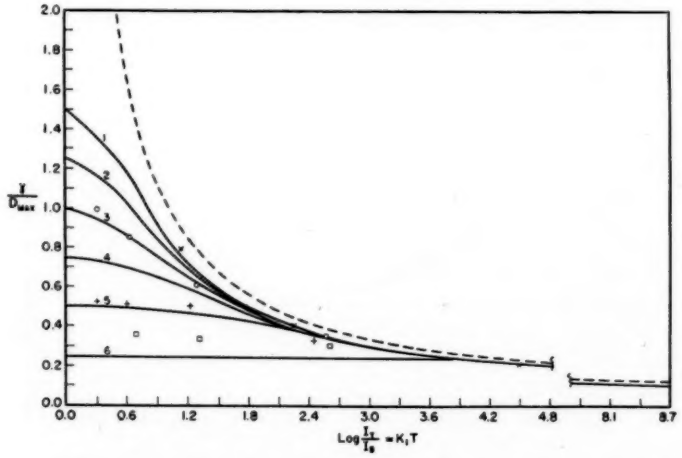

FIG. 7. Comparison of experimental and theoretical $\gamma/D_{\max}$ values over a wide range of $\log I_T/I_B$ values for several layers of emulsions.

Symbol	Emulsion	Wave-length	Thickness	Development time (minutes)
×	I	4200A	1, 2, and 4 layers	5
○	I	4800A	1, 2, 4, and 8 layers	5
+	II	4800A	1, 2, 4, and 8 layers	5
□	III	4800A	1, 2, and 4 layers	6

To obtain the composite H. and D. curves from which the γ/D_{max} values for different thicknesses of emulsion were obtained, the density curves of Fig. 8 were summed at each exposure step and these values divided by D_{max} for the group of layers. In this way the curves of Fig. 10 were obtained. Curves (a), (b), (c), and (d) refer, respectively, to 1-, 2-, 4-, and 8-layer thicknesses of emulsion I. The series of γ/D_{max} values obtained from these curves are plotted as the circles in Fig. 7. It may be seen that this series of points falls nearest to the theoretical curve, 3. Other experimental points plotted in Fig. 7 were obtained in a similar manner for other wave-lengths and other types of emulsions. In each case, the series of points fall in fair accord with the theoretical curves.

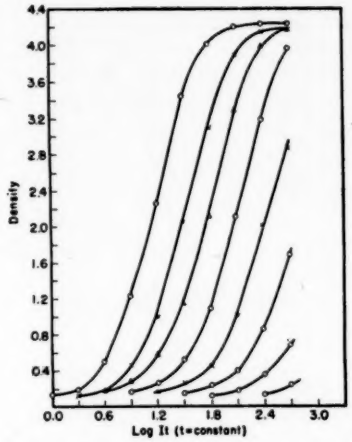

FIG. 8. H. and D. curves obtained by simultaneously exposing a series of eight emulsions piled one upon another. Emulsion I, wave-length 4800A.

VARIATION OF GAMMA WITH EMULSION THICKNESS

The curves of Fig. 7 show the variation of γ/D_{max} with emulsion thickness expressed in arbitrary units. It is not feasible to give the thickness in absolute units because the variation of absorption with thickness differs for different emulsions and therefore a different set of curves would be required for each emulsion. To use the diagram of Fig. 7 for any particular emulsion, it is necessary to determine the relation between $\log I_T/I_B$ and T for at least one value of T. In other words, the value of K_1 in the equation,

$$\log I_T/I_B = K_1 T,$$

must be determined. If this is done, the γ/D_{max} value for any other thickness, T, can be read directly from Fig. 7.

To obtain curves representing gamma as a function of emulsion thickness, the γ/D_{max} curves must be multiplied by D_{max}. Since D_{max} will vary with thickness, this must be taken into account. For any given emulsion, the variation of D_{max} may be assumed to vary linearly with thickness, thus:

$$D_{max} = K_2 T,$$

where K_2 is a constant. A straight sloping line representing this equation is shown in Fig. 11. If the ordinates of this straight line are multiplied by the various curves for γ/D_{max}, curves showing the relative variation of gamma with T are obtained. For each curve, 1→6, representing γ/D_{max}, there is a corresponding curve (1)→(6) for gamma, as shown in Fig. 11. For the curve representing $(\gamma/D_{max})_{max}$, the corresponding γ_{max} curve is a straight horizontal line. This is readily verified by noting that if the two equations,

$$(\gamma/D_{max})_{max} = 1/(\log I_T/I_B) = 1/K_1 T$$

and

$$D_{max} = K_2 T,$$

are multiplied, the resulting relation is

$$\gamma = K_2/K_1 = \text{constant}.$$

Curves (1)—(6), giving the variation of gamma with emulsion thickness, are shown in Fig. 11.

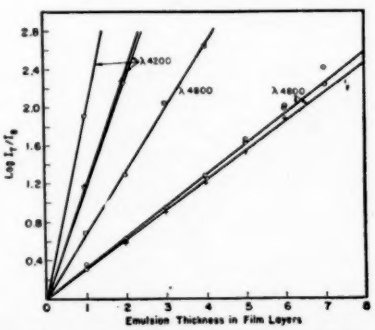

FIG. 9. Curves illustrating absorption of light by different numbers of emulsion layers piled one upon another.

Symbol	Emulsion
○	I
+	II
□	III

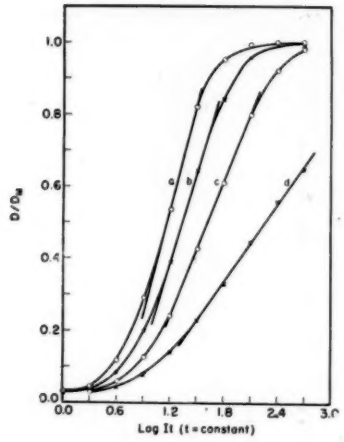

FIG. 10. H. and D. curves corresponding to very thick emulsions, derived by summation of density values for curves of type shown in Fig. 8. Emulsion I, wave-length 4800A.

Curve	Number of layers	γ/D_{max}	D_{max}	γ	log I_T/I_B	Development time (minutes)
a	1	0.99	4.2	4.16	0.30	5
b	2	0.85	8.4	7.14	0.61	5
c	4	0.61	1.68	10.24	1.28	5
d	8	0.35	3.36	11.76	2.56	5

These curves again are not in absolute units and cannot be so expressed until the constants of the emulsions, K_1 and K_2, are determined. The curves as drawn are general and apply to any type of emulsion. The diagram may be used quantitatively for a particular emulsion if one measurement is made as follows: Let an intensity-scale exposure to the desired wave-length be impressed on two layers of the emulsion placed, emulsion to emulsion, as shown in Fig. 6. For this exposure, the values of D_{max}, γ/D_{max}, and $\log I_T/I_B$ can be obtained as previously described. The γ/D_{max} value is then plotted on the γ/D_{max}-*vs.*-$\log I_T/I_B$ diagram. This procedure determines which γ/D_{max} curve applies to the emulsion under test. The gamma value measured for the emulsion may now be placed arbitrarily on the corresponding gamma-curve at the proper $\log I_T/I_B$ value. The relative gamma-values for other thicknesses may be read directly from the gamma curve thus selected.

In order to test the general correctness of the gamma-T curves of Fig. 11, a number of determinations of gamma with varying emulsion thickness were made and have been plotted on the theoretical diagrams shown. These gamma-values were obtained by means of exposures on different numbers of films piled on top of each other. The experimental points were obtained from the same experiments from which the points shown in Fig. 7 were obtained. The gamma-

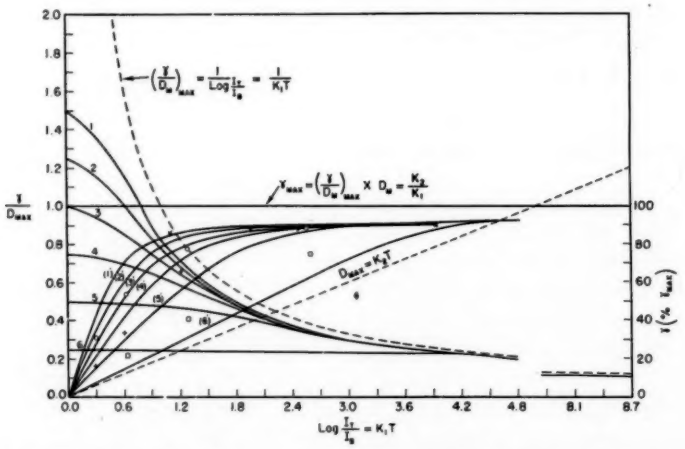

FIG. 11. Comparison of experimental and theoretical γ_{max} values for emulsions of different thicknesses.

Symbol	Emulsion	Wave-length	Thickness
×	I	4200A	1, 2, and 4 layers
○	I	4800A	1, 2, 4, and 8 layers
+	II	4800A	1, 2, 4, and 8 layers
□	II	4800A	1, 2, and 4 layers

values should, accordingly, follow the curves of corresponding numbers in the two diagrams of Figs. 7 and 11. Comparison of the results in these two figures shows this to be true. The values obtained with emulsion I, using λ4200A radiation, follow, in both cases, curve 1. The points for emulsion I, λ4800A radiation follow curve 3. The points for emulsion II, using λ4800A radiation, lie between curves 4 and 5, and the points for emulsion III lie between curves 5 and 6.

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 1 JANUARY, 1948

Optical Compensators for Measurement of Elliptical Polarization

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(Received July 28, 1947)

A detailed survey is given of the present-day knowledge of optical compensators. The compensators discussed are those of Babinet, Soleil, Rayleigh, De Forest Palmer, Brace, Szivessy, Senármont, and Richartz. Each instrument is described, the theory developed, the method of use for the measurement of small phase differences given, and reference made to the sensitivity and accuracy.

I. INTRODUCTION

IT is well known that if two coherent linear monochromatic waves, polarized in planes perpendicular to one another and of the same frequency, are combined, then the resultant wave is, in general, elliptically polarized. Adopting the usual Cartesian coordinate system, and assuming the wave normals to coincide with the positive Z axis, the components of the linearly polarized light vectors D_1 and D_2, along the axes may be represented by

$$D_{1x}=a\cos(\nu t-\alpha), \quad D_{1y}=0, \quad D_{1z}=0,$$
$$D_{2x}=0, \quad D_{2y}=b\cos(\nu t-\beta), \quad D_{2z}=0.$$

Hence the elliptically polarized wave has components

$$\left.\begin{aligned} D_X&=D_{1x}+D_{2x}=a\cos(\nu t-\alpha),\\ D_Y&=D_{1y}+D_{2y}=b\cos(\nu t-\beta),\\ D_Z&=D_{1z}+D_{2z}=0; \end{aligned}\right\} \quad (1)$$

a and b are the amplitudes of the waves, α and β are the phase constants, and ν the pulsatance. The difference $\delta=\beta-\alpha$ is the phase difference between the two waves.

In this article instruments used for the measurement of phase differences are discussed. Such instruments are called "compensators" because, in general, they consist of a system of doubly refracting plates which, if suitably placed in the paths of the waves to be examined, can compensate their phase difference.

Throughout the article it is assumed that monochromatic, plane light waves are used and that the phase difference to be measured (denoted by δ) is produced by a doubly refracting plate upon which linearly polarized light is incident from a polarizer. Unless otherwise stated, by the azimuth of a vibration direction is meant the azimuth with respect to the vibration direction of the polarizer, and by the azimuth of a crystal plate is meant the azimuth of the main direction of vibration of the faster ray. Except where otherwise stated the plate and polarizer can be replaced by elliptically polarized light produced by any means, e.g., metallic reflection.

In most of the older methods for the investigation of elliptically polarized light the change in intensity of a dark field of view was observed. This does not permit of the eye being most sensitive; a better method is to divide the field of view into two parts, each possessing moderate intensities, and to adjust until equal brightness of each is obtained. This is known as the half-shadow method and is essential for the measurement of very small phase differences; the accuracy of measurement of the individual methods depends, among other things, on the subjective photometric sensitivity of the observer, the in-

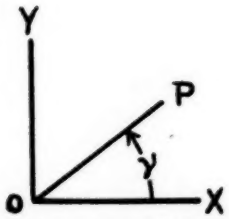

FIG. 1. OX and OY are the main vibration directions in the plate; OP, is the vibration direction of the incident wave.

tensity and the monochromatism of the light source.

According to the way in which the phase difference is measured, we may distinguish three general types of compensators: (1) the directly compensating type of which those of Babinet, Soleil, and De Forest Palmer are examples, (2) the compensator azimuth-measuring type to which belong the Brace compensator and the "simple half-shadow" compensator described by Szivessy, and (3), the analyzer azimuth-measuring type, examples of which are the "modified" Brace and modified Szivessy compensators and the De Senármont or quarter-wave compensator. The Rayleigh compensator and two compensators attributable to Richartz will also be described.

II. THE GENERAL THEORY

Before considering each compensator in detail it is necessary to discuss certain formulae to which constant reference will be made.

Let us consider the passage of linearly polarized light through a doubly refracting plane-parallel plate, making the assumption that the light falls normally on the plate in a direction *not* coincident with the optic axis. There originate in the interior of the plate two linearly, mutually perpendicular, polarized waves which are propagated with different velocities. On emerging from the plate the two waves combine to form, in general, an elliptically polarized wave. In Fig. 1, if OX and OY be the main vibration directions in the plate, and OP the vibration direction of the incident wave, then the incident light vector may be represented by $D_P = a\cos(\nu t - \epsilon)$, and the emergent components by

$$D_X = a\cos\gamma\cos(\nu t-\alpha),$$
$$D_Y = a\sin\gamma\cos(\nu t-\beta), \quad \text{(cf. Eq. 1)},$$

where γ is the angle between OP and OX $(-\pi/2 \leqslant \gamma \leqslant +\pi/2)$. This ignores any intensity diminution caused by reflection at the boundary surfaces of the plate and by absorption.[1] For a plate of thickness d and a wave-length λ, the phase difference on emergence is given by

$$\delta = \beta - \alpha = 2\pi(d/\lambda)(\mu_y - \mu_x), \qquad (2)$$

where μ_x and μ_y are the refractive indices of rays having vibrations along OX and OY, respectively. $\mu_y - \mu_x$ is called the birefringence; $\partial(\mu_y-\mu_x)/\partial\nu$ is the dispersion of the double refraction.

Several cases of importance arise depending upon the values chosen for δ and γ.

(a) $\gamma = 0$ or $\pm\pi/2$. The emergent wave is plane polarized in the same vibration plane as before.

(b) $\pi/4 > \gamma > 0$, $\delta = \pm(2n+1)\pi/2$ $(n = 0, 1, 2, \cdots)$. The emergent wave is elliptically polarized, the axes coinciding with the main vibrations of the crystal plate.

(c) $\gamma = \pm\pi/4$, δ arbitrary. In this case the axes of the elliptically polarized wave are parallel and perpendicular to the vibration direction of the incident wave. For the special case where $\delta = \pm(2n+1)\pi/2$ $(n = 0, 1, 2, \cdots)$ a circularly polarized wave emerges, and if d is such that $n = 0$, the plate is called a quarter-wave plate for the wave-length used.

(d) γ arbitrary, (a) $\delta = \pm 2n\pi$, (b) $\delta = \pm(2n+1)\pi$ $(n = 0, 1, 2, \cdots)$. In both cases the emergent wave is linearly polarized. For case (a) the azimuth is $+\gamma$; for case (b) the azimuth is $-\gamma$, both measured with respect to the main vibration direction OX. If d is such that $\delta = \pm\pi$, the plate is called a half-wave plate for the wave-length used.

For our purpose it will be necessary to consider a system of three doubly refracting plates situated between two linearly polarizing devices. The necessary parameters are shown in Fig. 2 and defined in the legend.

If the intensity of the light emerging from the polarizer is taken as unity, then that emerging from the analyzer is given by[2]

[1] For a full account of the influence of reflections on a doubly refracting plate see F. Gabler and P. Sokob, Zeits. f. Physik **116**, 47 (1940). The effect of absorption which is negligible is discussed by M. Berek, Ann. d. Physik **58**, 165 (1919).

[2] G. Szivessy and W. Herzog, Zeits. f. Instrumentenk. **57**, 53 (1937). For alternative forms see F. Gabler and P. Sokob, Zeits. f. Instrumentenk **58**, 302 (1938). For a generalized intensity formula for a system of n plates see Hsien-Yü Hsü, M. Richartz, and Yüng-K'ang Liang, J. Opt. Soc. Am. **37**, 99 (1947).

$$J_3=\cos^2\phi+4\sin2\gamma_1\sin2(\varphi-\gamma_3)\cos2(\gamma_2-\gamma_1)\cos2(\gamma_3-\gamma_2)\sin^2\delta_1/2\sin^2\delta_2/2\sin^2\delta_3/2$$
$$+\sin2\gamma_1\sin2(\varphi-\gamma_1)\sin^2\delta_1/2+\sin2\gamma_2\sin2(\varphi-\gamma_2)\sin^2\delta_2/2$$
$$+\sin2\gamma_3\sin2(\varphi-\gamma_3)\sin^2\delta_3/2-\sin2\gamma_1\sin2(\varphi-\gamma_3)[\cos2(\gamma_2-\gamma_1)\sin^2\delta_1/2\sin\delta_2\sin\delta_3$$
$$+\sin^2\delta_2/2\sin\delta_3\sin\delta_1+\cos2(\gamma_3-\gamma_2)\sin^2\delta_3/2\sin\delta_1\sin\delta_2]$$
$$+2[\sin2\gamma_1\sin2(\varphi-\gamma_2)\sin\delta_1/2\sin\delta_2/2\{\cos\delta_1/2\cos\delta_2/2-\cos2(\gamma_2-\gamma_1)\sin\delta_1/2\sin\delta_2/2\}$$
$$+\sin2\gamma_2\sin2(\varphi-\gamma_3)\sin\delta_2/2\sin\delta_3/2\{\cos\delta_2/2\cos\delta_3/2-\cos2(\gamma_3-\gamma_2)\sin\delta_2/2\sin\delta_3/2\}$$
$$+\sin2\gamma_1\sin2(\varphi-\gamma_3)\sin\delta_3/2\sin\delta_1/2\{\cos\delta_3/2\cos\delta_1/2-\cos2(\gamma_1-\gamma_3)\sin\delta_3/2\sin\delta_1/2\}]. \quad (3)$$

The intensity with two plates ($\gamma_3=0$; $\delta_3=0$) is, therefore,†

$$J_2=\cos^2\varphi+\sin2\gamma_1\sin2(\varphi-\gamma_1)\sin^2\delta_1/2+\sin2\gamma_2\sin2(\varphi-\gamma_2)\sin^2\delta_2/2$$
$$+2\sin2\gamma_1\sin2(\varphi-\gamma_2)\sin\delta_1/2\sin\delta_2/2\{\cos\delta_1/2\cos\delta_2/2-\cos2(\gamma_2-\gamma_1)\sin\delta_1/2\sin\delta_2/2\}, \quad (4a)$$

or

$$J_2=\cos^2\varphi+\sin2\gamma_1\cos2(\varphi-\gamma_2)\sin2(\gamma_2-\gamma_1)\sin^2\delta_1/2$$
$$+\cos2\gamma_1\sin2(\varphi-\gamma_2)\sin2(\gamma_2-\gamma_1)\sin^2\delta_2/2$$
$$+\sin2\gamma_1\sin2(\varphi-\gamma_2)\cos^2(\gamma_2-\gamma_1)\sin^2[(\delta_1+\delta_2)/2]$$
$$-\sin2\gamma_1\sin2(\varphi-\gamma_2)\sin^2(\gamma_2-\gamma_1)\sin^2[(\delta_1-\delta_2)/2]. \quad (4b)$$

For one plate only ($\gamma_2=\gamma_3=0$; $\delta_2=\delta_3=0$),

$$J_1=\cos^2\varphi+\sin2\gamma_1\sin2(\phi-\gamma_1)\sin^2\delta_1/2. \quad (5)$$

In many cases we shall deal with crossed polarizer and analyzer i.e., $\phi=\pm\pi/2$, and the intensity J_3 becomes J_3^x where x indicates crossed polarizer and analyzer.

$$J_3^x=4\sin2\gamma_1\sin2\gamma_3\cos2(\gamma_2-\gamma_1)\cos2(\gamma_3-\gamma_2)\sin^2\delta_1/2\sin^2\delta_2/2\sin^2\delta_3/2$$
$$+\sin^22\gamma_1\sin^2\delta_1/2+\sin^22\gamma_2\sin^2\delta_2/2+\sin^22\gamma_3\sin^2\delta_3/2$$
$$-\sin2\gamma_1\sin2\gamma_3[\cos2(\gamma_2-\gamma_1)\sin^2\delta_1/2\sin\delta_2\sin\delta_3$$
$$+\sin^2\delta_2/2\sin\delta_3\sin\delta_1+\cos2(\gamma_3-\gamma_2)\sin^2\delta_3/2\sin\delta_1\sin\delta_2]$$
$$+2[\sin2\gamma_1\sin2\gamma_2\sin\delta_1/2\sin\delta_2/2\{\cos\delta_1/2\cos\delta_2/2-\cos2(\gamma_2-\gamma_1)\sin\delta_1/2\sin\delta_2/2\}$$
$$+\sin2\gamma_2\sin2\gamma_3\sin\delta_2/2\sin\delta_3/2\{\cos\delta_2/2\cos\delta_3/2-\cos2(\gamma_3-\gamma_2)\sin\delta_2/2\sin\delta_3/2\}$$
$$+\sin2\gamma_1\sin2\gamma_3\sin\delta_3/2\sin\delta_1/2\{\cos\delta_3/2\cos\delta_1/2-\cos2(\gamma_1-\gamma_3)\sin\delta_3/2\sin\delta_1/2\}]. \quad (6)$$

From Eq. (4) for two plates

$$J_2^x=\sin^22\gamma_1\sin^2\delta_1/2+\sin^22\gamma_2\sin^2\delta_2/2$$
$$+2\sin2\gamma_1\sin2\gamma_2\sin\delta_1/2\sin\delta_2/2\{\cos\delta_1/2\cos\delta_2/2-\cos2(\gamma_2-\gamma_1)\sin\delta_1/2\sin\delta_2/2\}, \quad (7a)$$

or

$$J_2^x=-\sin2\gamma_1\cos2\gamma_2\sin2(\gamma_2-\gamma_1)\sin^2\delta_1/2+\cos2\gamma_1\sin2\gamma_2\sin2(\gamma_2-\gamma_1)\sin^2\delta_2/2$$
$$+\sin2\gamma_1\sin2\gamma_2\cos^2(\gamma_2-\gamma_1)\sin^2[(\delta_1+\delta_2)/2]-\sin2\gamma_1\sin2\gamma_2\sin^2(\gamma_2-\gamma_1)\sin^2[(\delta_1-\delta_2)/2], \quad (7b)$$

and for one plate only between crossed analyzer and polarizer

$$J_1^x=\sin^22\gamma_1\sin^2\delta_1/2. \quad (8)$$

† Compare, G. Szivessy, *Handbuch der Physik* **19**, 924 (1928).

From Eq. (6) it follows that $J_3^x=0$ if

$$\sin 2\gamma_1 \sin\delta_1/2=\sin 2\gamma_2 \sin\delta_2/2=\sin 2\gamma_3 \sin\delta_3/2=0. \tag{9}$$

Further, if (1) $\gamma_2=\gamma_1$

$$\begin{aligned}J_3=\cos^2\varphi+\sin 2\gamma_1 \sin 2(\varphi-\gamma_1) \sin^2[(\delta_1+\delta_2)/2]+\sin 2\gamma_3 \sin 2(\varphi-\gamma_3) \sin^2\delta_3/2\\ +2 \sin 2\gamma_1 \sin 2(\varphi-\gamma_3) \sin[(\delta_1+\delta_2)/2] \sin\delta_3/2\\ \times\{\cos[(\delta_1+\delta_2)/2] \cos\delta_3/2-\cos 2(\gamma_3-\gamma_1) \sin[(\delta_1+\delta_2)/2] \sin\delta_3/2\},\end{aligned} \tag{10}$$

which (compare Eq. (4a)) gives a system behaving as two plates of phase differences $\delta_1+\delta_2$ and δ_3, respectively.

(2) $\gamma_2=\gamma_1+\pi/2$, $(-\pi/2\leqslant\gamma_1\leqslant 0)$. The system is then equivalent to two plates of phase differences $-\delta_1+\delta_2$ and δ_3, respectively.

(3) $\gamma_2=\gamma_1-\pi/2$, $(0\leqslant\gamma_1\leqslant\pi/2)$. The phase differences then being $\delta_1-\delta_2$ and δ_3, respectively. Similar results hold if $\gamma_2=\gamma_3$ (or $\gamma_2=\gamma_3\pm\pi/2$), but not if $\gamma_1=\gamma_3$ (or $\gamma_1=\gamma_3\pm\pi/2$).

Let us consider briefly the effect on the intensity if the sequence of the plates is altered. In general, two consecutive plates cannot be interchanged without altering the intensity. However, if the three plates 1, 2, and 3, respectively, are situated between crossed polarizer and analyzer, 1 and 3 can always be interchanged without affecting the intensity, and 2 can be interchanged with 1 and the intensity remain unaltered provided $\gamma_2=\gamma_1$ or $\gamma_2=\gamma_1\pm\pi/2$, while 2 can be interchanged with 3 if $\gamma_2=\gamma_3$ or $\gamma_2=\gamma_3\pm\pi/2$.

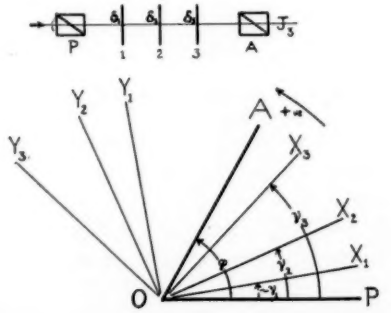

FIG. 2. The parameters. P, polarizer; A, analyzer; OP and OA are the vibration directions of the polarizer and analyzer, respectively; OX_1, OX_2, and OX_3 are the main vibration directions (fast) of the plates 1, 2, and 3; OY_1, OY_2, and OY_3 are the corresponding directions for the slow rays. δ_1, δ_2, and δ_3 are the phase differences introduced by the plates 1, 2, and 3. φ, γ_1, γ_2, and γ_3 are the azimuths of the analyzer and the plates 1, 2, and 3, respectively, measured from OP. J_3 is the intensity.

With two plates only between crossed polarizer and analyzer, their sequence is immaterial.

Finally it is necessary to be able to calculate the half-shadow sensitivity of the various compensators. If two intensities, J' and J'', are compared simultaneously with the eye, then the sensitivity of the latter may be defined as[3]

$$S=|(J'-J'')/(J'+J'')|.$$

Let us assume that for any individual eye there is a definite value of S, denoted by $\bar{S}$, at which the eye is most sensitive. If p is any independent parameter of the half-shadow apparatus, the variation Δp of which causes a variation in the intensities J' and J'', and p_0 the parameter value for which $J'=J''=J_0$, then

$$S=\frac{|(\partial/\partial p)(J'-J'')|_{p=p_0}}{2J_0}\cdot|\Delta p|=\tfrac{1}{2}s|\Delta p|,$$

where

$$s=\frac{|(\partial/\partial p)(J'-J'')|_{p=p_0}}{J_0}. \tag{11}$$

Now if $J'=J''$—a position we shall call the half-shadow position—S will be zero. The greater the factor s the more quickly will S approach the value $\bar{S}$ for a small change Δp. This quantity s is called the half-shadow sensitivity of the apparatus which should therefore be high. Although the value of $\bar{S}$ is dependent to some extent on the intensity of the field of view, we shall assume that for moderate intensities it has a constant value.

The conditions for maximum sensitiveness for the matching of two uniformly illuminated areas might well be mentioned here. Firstly, the areas should be contiguous; secondly, the matching field should subtend an area of at least 2° in the visual field; thirdly, the work should be done at moderate intensities.

[3] G. Szivessy, *Handbuch der Physik* 19, 926 (1928).

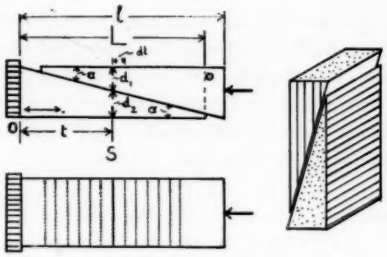

FIG. 3. The Babinet compensator.

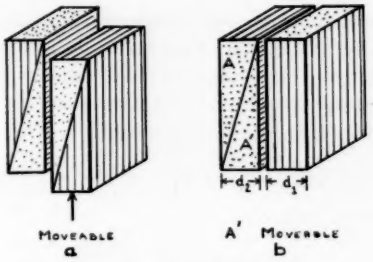

FIG. 4. (a). The Bravais compensator.
(b). The Soleil compensator.

III. COMPENSATORS

The Babinet Compensator[4]

The Babinet compensator was first developed to a high degree of accuracy by Jamin. It is used in conjunction with an analyzer and consists of two quartz wedges, usually of equal angle but not necessarily so, placed with their hypotenuses in contact so that together they form a plane-parallel plate: the plate thickness can be varied by sliding one wedge along the common interface by aid of a micrometer screw (see Fig. 3). The optic axes in the two plates are at right angles; their azimuths with respect to the edges of the wedges are of no importance, but for ease of cutting one generally has these axes parallel or perpendicular to the edge of the wedge. In front of the fixed wedge a fine cross-hair is situated upon which an eyepiece can be focused through the analyzer.

Theory. For the theory of the instrument let us assume that the compensator is in azimuth k. The light will be resolved into two rays traveling with different velocities in the wedges, the slower ray in the first wedge becoming the faster ray in the second wedge and *vice versa*. Assume also that there is no dispersion of double refraction.

Consider a section S, parallel to the wedge edges and perpendicular to the boundary planes. If d_1, d_2 are the thicknesses, Δ_1 and Δ_2 the phase differences introduced by the wedges at this section then, by Eq. (2)

$$\Delta_1=(2\pi/\lambda)d_1(\mu_\epsilon-\mu_0),$$
$$\Delta_2=(2\pi/\lambda)d_2(\mu_0-\mu_\epsilon),$$

where μ_ϵ and μ_0 are the refractive indices for the slow and fast rays, respectively. The resultant phase difference, κ, at this section is, therefore, given by

$$\kappa=\Delta_1+\Delta_2=(2\pi/\lambda)(\mu_\epsilon-\mu_0)(d_1-d_2). \quad (12)$$

The compensator may be treated as a single plate introducing this phase difference.

Taking into account reflection losses at the boundary surfaces then the phase difference will be $\kappa+C$, where C is an additive constant.

If now the value of (d_1-d_2) is such that the phase difference is $\pm 2n\pi$ or $\pm(2n+1)\pi$, $(n=0, 1, 2, \cdots)$, we have the case of linearly polarized light discussed in d of Section II, whereas for all other phase differences the emergent light is, in general, elliptically polarized. Ignoring reflection losses, for the compensator between crossed polarizer and analyzer, by Eq. (8) the intensity of the emergent wave in section S is $J_1^x=\sin^2 2k\sin^2(\kappa/2)$ which is zero when $\kappa=\pm 2n\pi$ or

$$d_1-d_2=\pm n\lambda/(\mu_\epsilon-\mu_0), \quad (13)$$

and a maximum $\sin^2 2k$ when $\kappa=\pm(2n+1)\pi$ or

$$d_1-d_2=\pm\frac{(2n+1)}{\mu_\epsilon-\mu_0}\lambda \quad (14)$$

for all integral values of n.

Hence the field of view is a system of parallel, equidistant, black interference fringes separated by bright fringes. The effect of reflection losses, if the amplitude variation is neglected, is simply to shift the fringes slightly, the separation remaining the same.

The difference in intensity between the dark and bright fringes is $\sin^2 2k$, which is a maximum if $k=\pm\pi/4$; it is best, therefore, to use the compensator in this azimuth.

[4] A. Bravais, Comptes rendus **32**, 115 (1851); G. Szivessy, Zeits. f. Physik **29**, 372 (1924).

The distance between any two fringes may be found from Eq. (13), for, since with reference to Fig. 3, $d_1 = t \tan\alpha$ and $d_2 = (l-t)\tan\alpha$, where α is the wedge angle, t the distance of S from a suitable origin 0, we may write,

$$d_1 - d_2 = (2t-l)\tan\alpha = \pm n\lambda/(\mu_\epsilon - \mu_0). \quad (15)$$

Differentiating:

$$2dt \cdot \tan\alpha = \pm \frac{\lambda}{(\mu_\epsilon - \mu_0)} dn,$$

i.e., $dt = \pm(\lambda/2\tan\alpha(\mu_\epsilon - \mu_0))$ for $dn = 1$, (16)

where dt is the required distance. This distance corresponds to a phase difference of 2π or path difference λ. It should be noted that a wedge movement of dt means that the fringe system moves unchanged through a distance $dt/2$.

Before use it is necessary to calibrate the instrument so that the phase difference, m, corresponding to one drum division is known. This may be carried out by setting the cross-wires on two consecutive dark fringes and noting the drum readings p_1 and p_2, respectively. To the drum difference $p_1 - p_2$ corresponds a phase difference of $\pm 2\pi$ which gives

$$m = \pm 2\pi/(p_1 - p_2). \quad (17)$$

A more accurate value can be obtained by taking a series of settings, say over ten fringes, and plotting a graph of drum readings against fringe number. The slope of the resultant straight line gives the required result.

Method of Use. To use the Babinet compensator, it is set in azimuth $\pm\pi/4$ and between crossed polarizer and analyzer and the cross-wire is set on any dark fringe (drum reading p_0); the phase difference κ_0 at this section must satisfy the equation $\kappa_0 = \pm 2n\pi$, where n has any integral value.

The crystal plate of unknown phase difference δ is now introduced in azimuth $\pm\pi/4$, whereupon the resulting phase difference at the section is $\kappa_0 + \delta$ and the fiducial dark fringe is laterally displaced. By suitable adjustment of the drum the fringe can be returned to its original position, where now $\kappa_1 + \delta = \pm 2n\pi$, and where again n has any integral value, κ_1 is the new compensator phase difference at the section, and p_1 is the new drum reading. Then $\delta = \kappa_0 - \kappa_1$ which, since the instrument is calibrated, is easily found.

From Eq. (12) we find that if $d_1 = d_2$, $\kappa = 0$, i.e., at the center, there is zero phase retardation. It is this central dark fringe which is used as the fiducial fringe in the above procedure and can easily be found by using white light illumination, in which case it is the only black fringe; the others are colored.

The sensitivity of the Babinet compensator depends directly upon the wedge angle, for if x is the wedge displacement corresponding to one drum division, then the corresponding phase difference κ is given by

$$\kappa = 2\pi x \tan\alpha(\mu_\epsilon - \mu_0)/\lambda.$$

It follows, therefore, that the sensitivity is greater the smaller α, but in practice, for very small angles the fringes are too broad to permit accurate readings. According to Szivessy the best size is about 30′ for the middle spectral region.[5] For quartz: $\mu_\epsilon = 1.55335$, $\mu_0 = 1.54424$. Using a screw of pitch 0.5 mm with a drum divided into 50 divisions, a lower limit for the measurable phase difference of about $1.4 \times 10^{-3} \cdot 2\pi$ is possible for a wave-length of 5890A. Szivessy quotes values from $7 \times 10^{-3} \cdot 2\pi$ to $1 \times 10^{-3} \cdot 2\pi$ over the visible region.

The Soleil Compensator[6]

Bravais obtained a compensator giving a uniform field of view instead of the fringe system of Babinet by combining two identical Babinet compensators as shown (Fig. 4a). This assembly is equivalent to a plate whose thickness is proportional to the thickness of the movable compensator. Such a compensator required four quartz plates. Biot used three plates to produce the same effect, his arrangement consisting of a plane-parallel plate placed on an Arago compensator (Fig. 4b).[7] This is identical with the Soleil compensator which we shall now describe.

This instrument consists of two adjustable quartz wedges, AA^1, of equal angle whose optic axes are parallel and which together form a plane-parallel plate; these two wedges are combined with a plane-parallel plate of quartz whose optic axis is at right angles to the optic axes of the

[5] G. Szivessy, *Handbuch der Physik* **19**, 941 (1928).
[6] Soleil, Comptes rendus, **21**, 426 (1845).
[7] M. E. Mascart, *Traité d'Optique* (Gauthier-Villars, Paris, 1891), Vol. 2, p. 61.

wedges so that the effective thickness is the difference between the thickness of the single plate and the sum of the thicknesses of the wedges, i.e., the combination is equivalent to a single plate. One of the wedges can be displaced by a micrometer screw provided with a graduated drum (a pitch of 0.5 mm with 100 drum divisions is a typical figure). The instrument is used in conjunction with an analyzer and observations are carried out by means of a telescope focused at infinity.

Theory. Following the same treatment as with the Babinet, the resultant phase difference produced by passage through the instrument is (compare Eq. (12))

$$\kappa=(2\pi/\lambda)(\mu_\epsilon-\mu_0)(d_1-d_2),$$

where d_1 is the fixed thickness of the plate and d_2 the sum of the thicknesses of the wedges and is variable. This expression, however, differs from Eq. (12) in that it holds for all sections and the field is therefore uniform.

With the compensator between crossed polarizer and analyzer, complete darkness of the field of view occurs for (Compare Eq. (13)) $\kappa=\pm 2n\pi$, or

$$d_1-d_2=\pm n\lambda/(\mu_\epsilon-\mu_0), \quad (n=0, 1, 2, \cdots), \quad (18)$$

and maximum brightness for (Eq. (14)), $\kappa=\pm(2n+1)\pi$, or

$$d_1-d_2=\pm\frac{(2n+1)}{\mu_\epsilon-\mu_0}\cdot\lambda \quad (n=0, 1, 2, \cdots).$$

Again it is best to use the compensator in azimuth $\pm\pi/4$.

Method of Use. The method of using the compensator is precisely the same as that with the Babinet but, instead of observations on a fringe, adjustments are made to complete darkness of field.

The sensitivity of the instrument, as with the Babinet, depends upon the wedge angle and is greater the smaller this angle, but too small an angle means that considerable drum movement is required before the eye can detect a change in intensity. The sensitivity varies from $7\times10^{-3}\cdot 2\pi$ to $1\times10^{-3}\cdot 2\pi$ for wedge angles of about 30°.

Use in Conjunction with Half-Shadow Plate. Although it is possible to increase the sensitivity by a Savart plate[8] placed between the compensator and the analyzer and suitably orientated it is best to use half-shadow methods.

Half-shadow devices for use with a Soleil have been described by Bravais, Zehnder, Biernacki, Zahrzewski, and Koenigsberger[9] but a device of variable sensitivity, worked out by Szivessy,[10] supersedes these. This consists of a very thin plane-parallel plate, usually of mica, covering half the field of view, and placed as near to the analyzer as possible; the plate can be rotated in its own plane. If the azimuths of the compensator and half-shade plate are $\pm\pi/4$ and h, respectively, their phase differences κ and η, then the intensity J_1^x of that half of the field not covered by the half-shade is, by Eq. (8), ($\gamma_1=\pm\pi/4$; $\delta_1=\kappa$),

$$J_1^x=\sin^2\kappa/2, \quad (19)$$

whilst the intensity J_2^x of the remaining half of the field of view is, by Eq. (7a) ($\gamma_1=\pm\pi/4$, $\gamma_2=h$; $\delta_1=\kappa$, $\delta_2=\eta$),

$$J_2^x=\sin^2\kappa/2+\sin^2 2h\,\sin^2\eta/2 \pm 2\sin 2h\,\sin\kappa/2\,\sin\eta/2 \times\{\cos\kappa/2\,\cos\eta/2\mp\sin\kappa/2\,\sin\eta/2\,\sin 2h\}. \quad (20)$$

These are equal ($J_1^x=J_2^x$) if either the half-shadow azimuth, h_0, satisfies

$$\sin 2h_0=0,$$

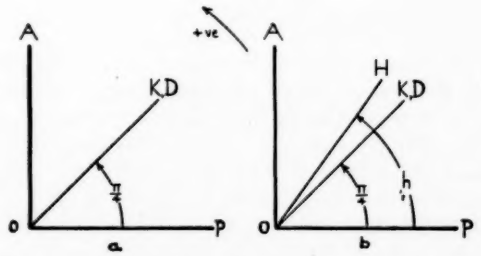

FIG. 5. Vibration directions for (a) Babinet and Soleil compensators, (b) Soleil with half-shadow plate. *OP* and *OA* are the vibration directions of the polarizer and analyzer, respectively. *OD*, *OH*, and *OK* are the vibration directions for the plates *D*, *H*, and *K*, respectively.

[8] A composite plate consisting of two equally thick plates, usually of quartz cut at $\pi/4$ to the optical axis, lying on top of each other with their principal planes at right angles. See G. Szivessy, *Handbuch der Physik* **19**, 942 (1928).

[9] Bravais, Zehnder, Biernacki, Zahrzewski, and Koenigsberger, *Handbuch der Physik* **19**, 943 (1928).

[10] G. Szivessy, Zeits. f. Physik **29**, 372 (1924).

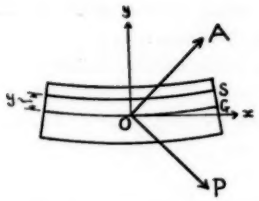

FIG. 6. The Rayleigh compensator. *OP* and *OA* are the vibration directions of the polarizer and analyzer, respectively. *G* is the neutral layer in azimuth $\pi/4$.

or the compensator azimuth, κ_0, is given by

$$\tan\kappa_0 = \mp\sin 2h \tan\eta/2. \qquad (21)$$

This last equation gives the essential half-shadow positions. If we now introduce an "effective phase difference $\bar{\eta}$" of the half-shadow plate, i.e., a phase difference dependent on the actual value η and the azimuth h such that

$$\tan\bar{\eta}/2 = \mp\tan\kappa_0 = \sin 2h \tan\eta/2, \qquad (22)$$

then

$$\kappa_0 = \pm 2n\pi \mp \bar{\eta}/2, \quad (n=0, 1, 2, \cdots). \qquad (23)$$

Hence, the rotation of the drum between two successive half-shadow positions corresponds to a phase difference of $\pm 2\pi$. In Eqs. (20)–(23) where the double sign occurs, the upper holds for $\gamma_1 = +\pi/4$, the lower for $\gamma_1 = -\pi/4$.

The half-shadow sensitivity s may be found from Eqs. (11), (19), (20), (22) and is directly proportional to $\cot\bar{\eta}/4$ which is greater the nearer $\bar{\eta}/4$ is to $\pm n\pi (n=0, 1, 2, \cdots)$.

In practice, $\bar{\eta}$ is made as near zero as possible for then the half-shadow position lies near the dark zero position of the compensator (compare Eq. (18)). Of course, η, is fixed but $\bar{\eta}$ can be made small by suitable choice of azimuth, the most suitable value being found for the particular observer by trial.

In taking observations the microscope is sharply focused on the dividing line of the half-shadow plate and the calibration and measurement of unknown phase differences are the same as with the ordinary Soleil compensator without the half-shadow device, adjustments being made to half-shadow positions. Figure 5 shows the vibration directions for the compensators.

The lower limit of measurement now possible for $\alpha = 30'$ is about $5\times10^{-4}\cdot 2\pi$ to $7\times10^{-5}\cdot 2\pi$; for smaller values of α the sensitivity is still greater.

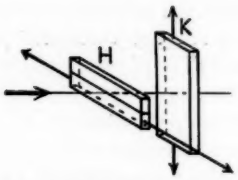

FIG. 7. Schematic arrangement of the De Forest Palmer compensator. *H*, half-shadow plate; *K*, compensator plate.

The Rayleigh Compensator[11]

This compensator consists of an optically isotropic glass rod of rectangular cross section placed in front of an analyzer. The beam is held horizontally on two fixed supports and bent by a small load. The layer not influenced by the bending—the so-called neutral layer—remains isotropic while on both sides double refraction of opposite sign appears; the main vibration directions lie parallel and perpendicular to the direction of principal stress. For suitable orientations a system of fringes appears, and observation is carried out with a telescope having a micrometer eyepiece with a vertical scale.

Theory. In developing the theory a coordinate system of axes is fixed; the x axis at the neutral layer parallel to the longitudinal edges of the rod; the positive y axis upwards and perpendicular to the x axis (see Fig. 6). The phase difference in a layer S, at a distance y from the neutral layer and parallel to it, is $\Delta = py$, where p is proportional to the applied load. If now the neutral layer is in azimuth $\pm\pi/4$, between crossed polarizer and analyzer the phase difference here will be zero ($y=0$) and the field of view will be crossed by a dark fringe. On introducing the plate of unknown phase difference, δ, in azimuth $\pm\pi/4$, the total phase difference at the neutral layer will be δ, and hence the black fringe will move to a layer whose phase difference neutralizes δ i.e., at a layer distance Y from the neutral layer,

$$\therefore \quad \delta = -pY. \qquad (24a)$$

In using the compensator the telescope is focused on the central fringe (this can easily be found by substituting white light for monochromatic light) and the eyepiece reading taken (y_1). After the introduction of the plate D, the new position of the fringe is found (reading y_2).

[11] Lord Rayleigh, Phil Mag **4**, 680 (1902); Sci. Pap. **5**, 64 (1905).

Then

$$\delta = -p(y_2 - y_1), \tag{24b}$$

which determines δ if p is previously determined by a preliminary calibration with a plate of known phase difference.[12] The sensitivity of the compensator can be varied by altering the load and the distance between the supports. Phase differences of about $6\times10^{-5}\cdot 2\pi$[13] can be measured, but by using a half-shadow device this may be increased.

Compensator of De Forest Palmer[14]

The De Forest Palmer compensator (Fig. 7) consists of a half-shadow plate, H, and a compensator plate, K, situated between a polarizer and an analyzer. The half-shadow plate is made up of two strain-free glass strips ($25\times4.7\times0.226$ mm), and so mounted that each strip covers half the field of view. One of the strips can be subjected to a pure tensile stress; the other strip is kept strain free and can be adjusted to lie in a plane which is parallel and adjacent to that of the first. The compensator plate ($25\times11\times0.226$ mm) covers the whole field of view and is also subjected to pure tensile stress, but in a direction perpendicular to that of H. The strains in the slips are produced by springs and the magnitudes of the tensions controlled by micrometer screws. For taking observations, a short-focus, low power observing telescope is provided which is focused on the dividing line of H.

Theory. The nomenclature used in developing the theory is given in Fig. 8. Since glass under tension behaves as a positive uni-axial crystal with the optic axis in the direction of the applied stress, the half-shade and compensating plates are equivalent to crossed positive doubly refracting plates of variable thickness.

Consider now the half-shadow and compensator plates stressed to produce phase differences η and κ, respectively.

The intensity J_2 of the half of the field of view covered by two birefringent plates is, by Eq. (4b),

$$(\gamma_1 = k \pm \pi/2,\ \gamma_2 = k;\ \delta_1 = \eta,\ \delta_2 = \kappa),$$

$$J_2 = \cos^2\varphi + \sin 2k \sin 2(\varphi - k) \sin^2[(\eta - \kappa)/2], \tag{25a}$$

and the intensity of the other half, by Eq. (5), is

$$J_1 = \cos^2\varphi + \sin 2k \sin 2(\varphi - k) \sin^2\kappa/2. \tag{25b}$$

Ignoring the solutions $k=0$ or ϕ, the intensity difference $J_2 - J_1$ is zero for a compensator phase difference κ_0 given by

$$\eta = 2\kappa_0. \tag{26a}$$

Suppose now the plate D, of unknown phase difference $\pm\delta$, is introduced in azimuth $k \pm \pi/2$, i.e., coinciding with the azimuth of the half-shadow plate. By Eq. (10) the three birefringent plates have the effect of two plates of phase differences $\pm\delta + \eta$ and κ, respectively, the upper or lower sign holding for a positive or negative double refraction. If κ_1 is the new compensator phase difference giving the half-shadow position, then

$$\eta = 2(\kappa_1 \pm \delta). \tag{26b}$$

This equation enables δ to be found. The final balance can be obtained by varying either η or κ, but it would appear that if η be kept fixed its value need not be known, for eliminating η from Eqs. (26a) and (26b)

$$\pm\delta = \kappa_0 - \kappa_1. \tag{27}$$

Although the half-shadow conditions are inde-

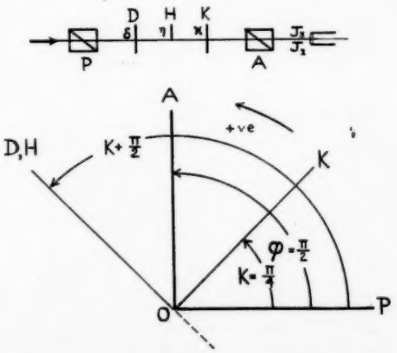

FIG. 8. The optical system and azimuths of the directions of vibration for the De Forest Palmer compensator. P, polarizer; A, analyzer (azimuth ϕ); D, plate under test; H, half-shadow plate; K, compensator plate (azimuth k); OP, OA, OD, OH, and OK, their respective vibration directions. δ, η, and κ phase differences produced by D, H, and K, respectively.

[12] By using this compensator in conjunction with a Soleil, the fringe displacement of the former can be compensated whence the drum reading will give δ directly.

[13] P. Zeeman and C. M. Hoogenboom, Physik. Zeits. **13**, 914 (1912).

[14] A. De Forest Palmer, Phys. Rev. **17**, 409 (1921); H. A. Boorse, Phys. Rev. **46**, 187 (1934).

pendent of the analyzer azimuth and compensator azimuth k, there are azimuths giving maximum half-shadow sensitivity. From Eqs. (11), (25a), (25b), and (26a) the half-shadow sensitivity is given by

$$s=\frac{\sin 2k \sin 2(\varphi-k) \sin\kappa}{\cos^2\varphi+\sin 2k \sin 2(\varphi-k) \sin^2\cdot\kappa/2}. \quad (28)$$

A maximum occurs for the conditions

$$\partial s/\partial\varphi=0, \quad \partial s/\partial k=0, \quad \text{and} \quad \partial s/\partial\kappa=0,$$

i.e.,

$$\varphi=\pi/2, \quad k=\pm\pi/4, \quad \text{and} \quad \kappa=0,$$

and

$$s_{\max} \text{ (excluding } \kappa=0)=\cot\kappa/2. \quad (29)$$

Before use, a calibration is necessary. The phase difference and tension in a glass slip are linearly related, and it is possible to find the number of micrometer divisions per unit tension and, hence, read off directly the phase difference. The slip is placed between crossed polarizer and analyzer and a $\lambda/4$ plate inserted nearest the analyzer in zero azimuth. The phase difference can be calculated from the angle of rotation necessary to produce extinction and a calibration effected.

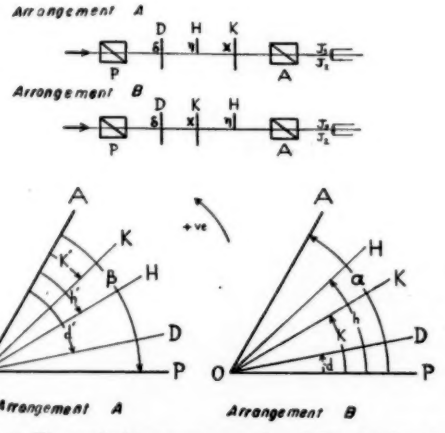

FIG. 9. The optical arrangements A and B and azimuths of the directions of vibration for the Brace compensator. P, polarizer; A, analyzer; D, plate under test; H, half-shadow plate; K, compensator plate. OP, OA, OD, OH, and OK, their respective vibration directions. δ, η, and κ are the phase differences produced by D, H, and K, respectively. In arrangement A the azimuths of D, H, K, and P are d', h', k', and β, respectively, measured from OA. In arrangement B the corresponding azimuths are d, h, k, and α, respectively, measured from OP. In the text $d=h=d'=h'=\pm\pi/4$.

Method of Use. To determine an unknown phase difference, produced say by a doubly refracting plate the apparatus is set up under conditions of maximum sensitivity (Eq. (29)), κ being made as small as possible. The micrometer reading p_0, corresponding to Eq. (26a), is taken; on insertion of plate D a new reading p_1 is obtained for the new half-shadow position. Then by Eq. 27

$$\pm\delta=p_0-p_1.$$

The limiting sensitiveness of the instrument is claimed to be as low as $5\times10^{-6}\cdot2\pi$ for a wavelength of 5840A provided the observer's eye is dark-adapted.[15]

The Brace Compensator[16]

The essential components of this instrument are two thin, plane-parallel plates of doubly refracting material (usually mica) used in conjunction with an analyzer. One plate, called the compensator plate, covers the whole field of view; the second plate, called the half-shadow plate, covers only half the field of view. Both plates are fixed on graduated circles, each capable of rotation by a micrometer screw; the azimuth of the half-shadow plate is usually fixed at $\pm\pi/4$. The phase difference produced by the compensator plate should be about $2\pi/60$ for wavelengths of the middle spectral region, while a suitable value for that of the half-shadow plate is between $2\pi/160$ and $2\pi/360$. Observation on the dividing line of the half-shadow plate is carried out by a magnifying glass or telescope.

If we consider the two possible arrangements A and B shown in Fig. 9, and assume for the present that the plate D is not in position, then, with crossed polarizer and analyzer, the sequence of the compensator plate and half-shadow plate is immaterial, i.e., arrangements A and B are identical. Further, if J_2^x and J_1^x are the intensi-

[15] In the original the half-shade and compensator springs produced tensions of 0.285 g and 2.04 g per micrometer division, respectively. If P_H and P_c are the tension expressed in micrometer divisions

$$\eta=2.00P_H\times10^{-6}, \quad \kappa=6.112P_c\times10^{-6};$$

possible maxima being $\eta=3\times54\times10^{-4}\cdot2\pi$ and $1.77\times10^{-4}\cdot2\pi$ whence the maximum value of the phase difference which can be measured is $\kappa_0=1.77\times10^{-4}\cdot2\pi$.

[16] D. B. Brace, Phil. Mag. **7**, 320 (1904); Phys. Rev. **18**, 70 (1904); *ibid.* **19**, 218 (1904); G. Szivessy, Zeits. f. Instrumentenk. **57**, 49 and 89 (1937).

ties of the fields of view covered and not covered by the half-shadow plate, then, assuming the azimuth of the half-shadow plate to be $\pm\pi/4$ from Eqs. (7) and (8),

$$J_2^x - J_1^x = \sin\eta/2\{\sin 2k \sin\kappa \cos\eta/2 \pm(1-2\sin^2 2k \sin^2\kappa/2)\sin\eta/2\}, \quad (30)$$

where k is the azimuth of the compensator plate. This expression is zero for compensator azimuths k_0 given by

$$\sin 2k_0 \sin\kappa \cos\eta/2 \pm(1-2\sin^2 2k_0 \sin^2\kappa/2)\sin\eta/2 = 0. \quad (31)$$

In using the compensator, however, to measure phase difference there is a most definite difference between arrangements A and B even with crossed polarizer and analyzer; for, supposing the phase difference δ produced by a doubly refracting plate is to be measured, then the sequence of the respective plates is no longer immaterial (see Fig. 10).[17]

The two arrangements have both been widely used and, although arrangement A was the original one worked out by Brace[16] his formulae lead to incorrect results; we shall discuss both cases, following closely the treatment due to Szivessy.[16]

In order to simplify the calculations, in arrangement A the azimuths will be measured with respect to the vibration direction of the analyzer, whereas in arrangement B measurements are taken from the vibration direction of the polarizer. The parameters are shown in Fig. 9 and defined in the legend; the parameter values to be substituted in Eq. (3) are, therefore, for arrangement A:

$$\varphi = -\beta, \quad \gamma_1 = -(\beta - d'), \quad \gamma_2 = -(\beta - h'), \quad \gamma_3 = -(\beta - k'); \quad \delta_1 = \delta, \quad \delta_2 = \eta, \quad \delta_3 = \kappa,$$

and for arrangement B:

$$\varphi = \alpha, \quad \gamma_1 = d, \quad \gamma_2 = k, \quad \gamma_3 = h; \quad \delta_1 = \delta, \quad \delta_2 = \kappa, \quad \delta_3 = \eta.$$

We shall, as did Brace, take the cases when the doubly refracting plate and the half-shadow plate

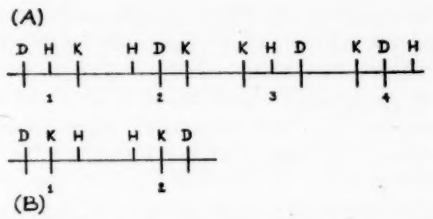

FIG. 10. Possible arrangements for the Brace compensator. D, plate under test; H, half-shadow plate; K, compensator plate. Arrangements $A(1)$, $A(2)$, and $B(2)$ are independent of the polarizer azimuth at the half-shadow position; arrangements $A(3)$, $A(4)$, and $B(1)$ are independent of the analyzer azimuth.

are both in the same azimuth $\pm\pi/4$, whence, from Eq. (3) and (4a), the difference in intensity of the two halves of the field of view for arrangement A is given by

$$J_3 - J_2 = \mp\cos 2\beta \sin\eta/2 \times\{\pm(1-2\sin^2 2k' \sin^2\kappa/2)\sin(\delta+\eta/2) + \sin 2k' \sin\kappa \cos(\delta+\eta/2)\}. \quad (32)$$

This expression is zero (half-shadow position) if one of the following conditions hold:

(a) $\cos 2\beta = 0$, (b) $\sin\eta/2 = 0$,

or the compensator azimuth $\bar{k}'$ satisfies

$$(c) \quad \pm(1-2\sin^2 2\bar{k}' \sin^2\kappa/2)\sin(\delta+\eta/2) + \sin 2\bar{k}' \sin\kappa \cos(\delta+\eta/2) = 0. \quad (33)$$

For arrangement B

$$J_3 - J_2 = \mp\cos 2\alpha \sin\eta/2[\pm\sin\delta(\cos\kappa \cos\eta/2 \mp\sin 2k \sin\kappa \sin\eta/2) + \cos\delta\{\sin 2k \sin\kappa \cos\eta/2 \pm(1-2\sin^2 2k \sin^2\kappa/2)\sin\eta/2\}], \quad (34)$$

which is zero if

(a) $\cos 2\alpha = 0$, (b) $\sin\eta/2 = 0$,

or the compensator azimuth $\bar{k}$ satisfies

$$(c) \quad \pm\sin\delta(\cos\kappa \cos\eta/2 \mp\sin 2\bar{k} \sin\kappa \sin\eta/2) + \cos\delta\{\sin 2\bar{k} \sin\kappa \cos\eta/2 \pm(1-2\sin^2 2\bar{k} \sin^2\kappa/2)\sin\eta/2\} = 0. \quad (35)$$

In Eqs. (32)–(35) the upper sign holds if the azimuth is $+\pi/4$, the lower sign if $-\pi/4$.

The essential conditions for equal intensity of both halves of the field of view are given by Eqs. (33) and (35). Equation (33) is independent of the polarizer azimuth β and Eq. (35) is inde-

[17] The effect of the sequence of the plates has been discussed in the introduction. The possible arrangements for the Brace compensator are shown in Fig. 10, where it can be seen that the essential difference between arrangements A and B is that in one case K never lies between H and D, in the other it always does.

pendent of the analyzer azimuth α. As we shall see later, however, the half-shadow sensitivity in arrangement A is dependent on the value of β and in arrangement B on the value of α. These facts give a practical advantage to arrangement B, for it is easier to rotate the analyzer rather than the polarizer.

With the plate D removed (i.e., $\delta=0$) the half-shadow condition for arrangement A, given by Eq. (33), takes the form

$$\pm(1-2\sin^2 2\bar{k}_0'\sin^2\kappa/2)\sin\eta/2 + \sin 2\bar{k}_0'\sin\kappa\cos\eta/2=0, \quad (36)$$

$\bar{k}_0'$ being the new half-shadow compensator azimuth. $\bar{k}'$ and $\bar{k}_0'$ have real values only if

$$|\tan(\delta+\eta/2)| \gtrless |\tan\kappa|. \quad (37)$$

Eliminating η from Eqs. (33) and (36),

$$\tan\delta = \mp\sin\kappa(\sin 2\bar{k}'-\sin 2\bar{k}_0')\left(\frac{1+2\sin 2\bar{k}'\sin 2\bar{k}_0'\sin^2\kappa/2}{(1-2\sin^2 2\bar{k}'\sin^2\kappa/2)(1-2\sin^2 2\bar{k}_0'\sin^2\kappa/2)\cdot}\right). \quad 0\lessgtr\delta\lessgtr 2\pi. \quad (38)$$

Similarly with arrangement B for $\delta=0$

$$\pm(1-2\sin^2 2\bar{k}_0\sin^2\kappa/2)\tan\eta/2+\sin 2\bar{k}_0\sin\kappa=0, \quad (39)$$

and $\bar{k}$ and $\bar{k}_0$ again have real values only if Eq. (37) holds. Eliminating η,

$$\tan\delta = \mp\sin\kappa(\sin 2\bar{k}-\sin 2\bar{k}_0)\left(\frac{1+2\sin 2\bar{k}\sin 2\bar{k}_0\sin^2\kappa/2}{\cos\kappa(1-2\sin^2 2\bar{k}_0\sin^2\kappa/2)+\sin 2\bar{k}\sin 2\bar{k}_0\sin^2\kappa}\right). \quad 0\lessgtr\delta\lessgtr 2\pi. \quad (40)$$

In Eqs. (36), (38), (39), and (40) the upper or lower signs hold if $d'=h'=d=h=+\pi/4$ or $-\pi/4$, respectively.

If we consider only small values of δ then Eqs. (38) and (40) approximate to

$$\delta = \mp\sin\kappa(\sin 2\bar{k}'-\sin 2\bar{k}_0') \quad (41)$$

and

$$\delta = \mp\tan\kappa(\sin 2\bar{k}-\sin 2\bar{k}_0), \quad (42)$$

from which we see that if κ is small enough to write $\sin\kappa=\tan\kappa$, without appreciable error, the two arrangements are identical.

We turn now to considerations of maximum half-shadow sensitivity for, although the half-shadow azimuth of the compensator plate in arrangement A is independent of the polarizer azimuth β, and in arrangement B independent of the analyzer azimuth α, there are values of β and α which give maximum half-shadow sensitivity.

From Eqs. (11), (3), and (4a) (with requisite substitutions), (33) and (35), respective half-shadow sensitivities s_A and s_B are given by

$$s_A = \frac{p'\cos 2\beta}{\cos^2\beta - F'\cos 2\beta + G'\sin 2\beta}, \quad (43)$$

$$s_B = \frac{p\cos 2\alpha}{\cos^2\alpha - F\cos 2\alpha + G\sin 2\alpha}, \quad (44)$$

where

$$p' = 4\sin\eta/2\sin\kappa/2\cos 2\bar{k}'\{\cos(\delta+\eta/2)\cos\kappa/2 \mp 2\sin 2\bar{k}'\sin(\delta+\eta/2)\sin\kappa/2\},$$

$$F' = \sin^2\delta/2+\sin 2\bar{k}'\sin\kappa/2(\sin 2\bar{k}'\sin\kappa/2\cos\delta\pm\cos\kappa/2\sin\delta),$$

$$G' = \tfrac{1}{2}\sin 4\bar{k}'\sin^2\kappa/2,$$

$$p = 4\sin\eta/2\sin\kappa/2\cos 2\bar{k}\{\cos(\delta+\eta/2)\cos\kappa/2 \mp 2\sin 2\bar{k}\cos\delta\sin\eta/2\sin\kappa/2\},$$

$$F = \sin^2\delta/2+\sin 2\bar{k}\sin\kappa/2(\sin 2\bar{k}\sin\kappa/2\cos\delta\pm\cos\kappa/2\sin\delta),$$

$$G = \cos 2\bar{k}\sin\kappa/2(\sin 2\bar{k}\sin\kappa/2\cos\delta\pm\cos\kappa/2\sin\delta).$$

When a double sign occurs in these expressions the upper holds for azimuth $+\pi/4$, the lower for azimuth $-\pi/4$. Equations (33) and (35) give $\bar{k}'$ and $\bar{k}$. Both expressions are proportional to $\kappa/(2\delta+\eta)$ for small values of $\delta+\eta/2$ and κ when β and α are almost equal to $\pm\pi/2$. Maximum sensitivity occurs for azimuths $\bar{\beta}$ and $\bar{\alpha}$ satisfying the equations $\partial s_A/\partial\beta=0$ and $\partial s_B/\partial\alpha=0$, respectively; i.e., for arrangement A

$$\sin 2\bar{\beta} = -\sin 4\bar{k}' \sin^2\kappa/2; \qquad (45a)$$

for arrangement B

$$\sin 2\bar{\alpha} = -\sin 4\bar{k} \sin^2\kappa/2 \cos\delta \mp \cos 2\bar{k} \sin\kappa \sin\delta. \qquad (45b)$$

If $\delta=0$ (plate D removed) these equations assume the form

$$\sin 2\bar{\beta}_0 = -\sin 4\bar{k}_0' \sin^2\kappa/2, \qquad (46a)$$

and

$$\sin 2\bar{\alpha}_0 = -\sin 4\bar{k}_0 \sin^2\kappa/2. \qquad (46b)$$

The solutions to Eqs. (45), (46) are of the form

$$2\varphi = \pm 2n\pi + 2\varphi_0 \quad \text{or} \quad \pm(2n+1)\pi - 2\varphi_0, \quad (n=0, 1, 2, \cdots), \qquad (47)$$

ϕ_0 being assumed positive, which means for a complete rotation of the analyzer or polarizer the four possible azimuths for maximum or minimum half-shadow sensitivity are:

$$\varphi_{01}=\varphi_0, \quad \varphi_{02}=\pi/2-\varphi_0, \quad \varphi_{03}=\pi+\varphi_0, \quad \varphi_{04}=3\pi/2-\varphi_0. \qquad (48)$$

These positions are shown in Fig. 11.[18] It is found that ϕ_{02} and ϕ_{04} correspond to maximum sensitivity. In practice these azimuths are easily distinguishable from the minimum of sensitivity, for in the latter the intensity of the field of view is great compared to that for maxima.

We should note that these azimuths corresponding to maximum half-shadow sensitivity do not correspond also to those giving a maximum or minimum intensity of the field of view. Since in using the Brace compensator the latter azimuths are not required we shall not discuss them further here.[19]

A further consideration of the expressions for the half-shadow sensitivity shows that in both arrangements increased sensitivity results if the phase difference, η, of the half-shadow plate decreases or that of the compensator plate increases.[20] The phase difference of the compensator plate is made small, despite the decreased sensitivity, because otherwise the azimuths $\bar{k}'$ and $\bar{k}_0'$ from Eqs. (33) and (36) and $\bar{k}$ and $\bar{k}_0$ from Eqs. (35) and (39) are almost identical.

Method of Use. Finally we turn to the experimental procedure for the determination of δ. In both arrangements the polarizer and analyzer are crossed and the azimuths of the half-shadow plate and the doubly refracting plate under test are set at $\pm\pi/4$. A provisional determination of the half-shadow azimuth of the compensator plate is made so that values $\bar{k}'$ and $\bar{k}$ are obtained by Eqs. (33) and (35), respectively. $\bar{\beta}$ and $\bar{\alpha}$ are then calculated by Eqs. (45). For arrangement A the polarizer is set in azimuth $\pm\pi/2-\bar{\beta}$, for arrangement B the analyzer is set in azimuth $\pm\pi/2-\bar{\alpha}$. These values are characterized by the fact that a small change in compensator azimuth results in a sudden intensity change in both halves of the field of view. The half-shadow azimuths $\bar{k}'$ and $\bar{k}$ are now accurately found in either arrangement by rotating the compensator plate through 2π to give four half-shadow azimuths (i.e., solution of Eqs. (45)). Thus for arrangement A:

$$k_1=\bar{k}', \quad k_2=\pi/2-\bar{k}', \quad k_3=\pi+\bar{k}', \quad k_4=3\pi/2-k', \qquad (49)$$

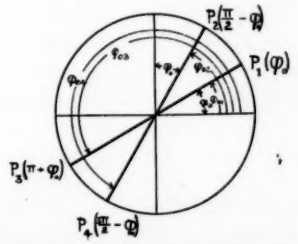

FIG. 11. Solutions of the equation $\sin 2\phi = X$ where X is a positive number.

[18] If ϕ_0 is negative, $2\phi=\pm 2n\pi-2\phi_0$ or $\pm(2n+1)\pi+2\phi_0$, $(n=0, 1, 2\cdots)$.

[19] For a detailed discussion see G. Szivessy, Zeits. f. Instrumentenk. **57**, 92 (1937).

[20] To obtain a half-shadow plate of very small difference which can also be varied, a plate of phase difference η can be used in azimuth $h(-\pi/2 \lesseqgtr h \lesseqgtr +\pi/2)$ differing from $\pm\pi/4$ so that the effective phase difference in this azimuth is $\eta=\pm\eta \sin 2h$, the positive value holding if $0 \lesseqgtr h \lesseqgtr +\pi/2$, the negative if $-\pi/2 \lesseqgtr h \lesseqgtr 0$. Such a plate was devised by Wedeneewa (Zeits. f. Instrumentenk. **43**, 17 (1923)), but its application is limited to cases where small phase differences are involved and, if arrangement A is used, the polarizer and analyzer must be crossed, thus precluding the use of the most favorable polarizer azimuth.

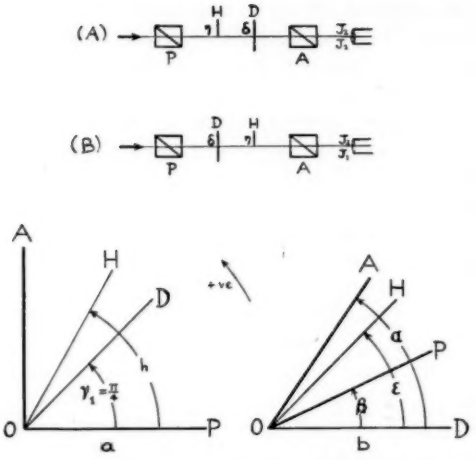

FIG. 12. The optical arrangements A and B and azimuths of the directions of vibration for the Szivessy and modified Szivessy compensators. P, polarizer; A, analyzer; D, plate under test; H, half-shadow and compensator plate; OP, OA, OD, OH their respective vibration directions. δ and η are the phase differences produced by D and H, respectively. In (a) (Szivessy) the azimuths are measured from OP. In (b) (modified Szivessy) the azimuths β, α, and ϵ of P, A, and H respectively, are measured from OD.

corresponding to readings p_1, p_2, p_3, and p_4 on the graduated circle of the compensator plate. $\bar{k}'$ is, therefore, given by[21]

$$2\bar{k}'=(\theta_1+\theta_2+\theta_3)/3, \tag{50}$$

where

$$\begin{aligned}\theta_1&=(\pi/2)-(p_2-p_1),\\ \theta_2&=(p_3-p_2)-(\pi/2),\\ \theta_3&=(\pi/2)-(p_4-p_3),\end{aligned} \tag{51}$$

and the criterion for correct adjustment is

$$p_3-p_1=p_4-p_2=\pi, \tag{52}$$

within the possible errors of observation. Similarly, $\bar{k}$, $\bar{k}_0'$, and $\bar{k}_0$ are determined, and δ calculated by substitution in Eqs. (38) or (40), respectively, or in the approximate Eqs. (41) and (42).

According to Szivessy, the Brace compensator can measure phase differences of magnitude $1\times10^{-4}\cdot2\pi$ within accuracy of 0.5 to 1 percent; under favorable conditions the limits are between $5\times10^{-5}\cdot2\pi$ and $3\times10^{-5}\cdot2\pi$.

[21] G. Szivessy, Zeits. f. Physik **54**, 594 (1929).

The Szivessy "Simple Half-Shade" Compensator[22]

This compensator is similar in many respects to the Brace compensator. It appears to be easier to use and equally sensitive in spite of lacking the advantage of a variable sensitivity which can be adjusted to suit the prevailing conditions.

The compensator, shown in Fig. 12 consists of a single plate, H, usually of mica or quartz, cut parallel to the optic axis, and an analyzer. This plate covers half the field of view and acts both as the half-shadow plate and the compensator plate; it can be rotated through 2π radians. The phase difference η of this half-shadow plate is chosen by the observer once the approximate magnitude of the phase difference to be measured is known; in all cases it lies between 0 and $\pi/2$. Observation on the dividing line of the field of view is carried out by a magnifying glass or telescope.

It should be pointed out that the compensator should be used only for determinations of phase differences lying near $2n\pi$ ($n=0, 1, 2, \cdots$) and is most efficient if δ differs only slightly from zero.

Theory. In considering the theory of this instrument we take the plate D under test to be fixed in azimuth $\pm\pi/4$. The polarizer and analyzer are crossed since this gives maximum half-shadow sensitivity, and so the sequence of the plates H and D is immaterial. In order, however, to get the field of view as large as possible, D is normally placed near the polarizer, i.e., arrangement B in figure.

If $J_2{}^x$ and $J_1{}^x$ are the intensities of the fields of view covered and not covered by the plate H, then by Eqs. (7a) and (8) ($\gamma_1=\pm\pi/4$, $\gamma_2=h$; $\delta_1=\delta$, $\delta_2=\eta$),

$$\begin{aligned}J_2{}^x=&\sin^2\delta/2+\sin^2 2h\,\sin^2\cdot\eta/2\\ &\pm2\sin2h\,\sin\eta/2\,\sin\delta/2\\ &\times\{\cos\delta/2\cos\eta/2\mp\sin\delta/2\sin\eta/2\sin2h\},\end{aligned} \tag{53}$$

$$J_1{}^x=\sin^2\delta/2. \tag{54}$$

For equal intensities of both halves of the field of view, the half-shadow azimuth of the compensator plate h_0 must satisfy the relationships:

$$\sin2h_0\doteq0, \tag{55a}$$

$$\tan\delta=\pm\sin2h_0\tan\eta/2,\quad(0\leqslant\delta\leqslant2\pi), \tag{55b}$$

[22] G. Szivessy and A. Dierkesmann, Ann. d. Physik **11**, 949 (1931).

where in the latter real values are possible only if

$$|\tan\eta/2| \geqslant |\tan\delta|. \qquad (56)$$

In Eqs. (53) and (55b) the upper or lower sign holds according to whether γ_1 is $+\pi/4$ or $-\pi/4$, respectively.

Let us now consider the factors controlling the half-shadow sensitivity which, from Eqs. (11), (53), (54), and (55b), is given by

$$s=2\left|\frac{\sin\eta}{\tan\delta/2}\right|\times\left|\left(1-\frac{\tan^2\delta}{\tan^2\eta/2}\right)^{\frac{1}{2}}\right|, \qquad (57)$$

s therefore increases the nearer δ is to $2n\pi$ and η to $(2n+1)\pi/2$ ($n=0, 1, 2, \cdots$). If, however, δ had any such value Eq. (55b) becomes $\sin 2h_0=0$, and if $\eta=(2n+1)\pi/2$, then for small values of δ, $\sin 2h_0$ is almost zero. δ should, then, differ slightly from $2n\pi$ and η is then chosen so that the inequality given by Eq. (56) holds, $|\sin\eta|$ is sufficiently large and h_0 is measurable.

The azimuths given by Eqs. (55) are not those corresponding to a maximum or minimum of intensity of the field of view. Although it is possible to determine these latter azimuths and hence calculate a value for δ, the method is less sensitive than the half-shadow method and has, therefore, been omitted.[23]

Method of Use. For the determination of an unknown phase difference δ, the plate is set in azimuth $\pm\pi/4$ between crossed polarizer and analyzer. The half-shadow plate is rotated through 2π radians whereupon eight half-shadow azimuths are obtained, four being given by the roots of Eq. (55a) and four from Eq. (55b). The latter are

$$h_{01}=h_0, \quad h_{02}=\pi/2-h_0,$$
$$h_{03}=\pi+h_0, \quad h_{04}=3\pi/2-h_0,$$

and if the corresponding readings on the graduated circle are P_1, P_2, P_3, and P_4, then

$$2h_0=(\theta_1+\theta_2+\theta_3)/3, \qquad (58)$$

where θ_1, θ_2, and θ_3 are defined by Eq. (51), and Eq. (52) gives the criterion for correct adjustment. δ is now calculated by substitution in Eq. (55b).

[23] G. Szivessy and A. Dierkesmann, Ann. d. Physik **11**, 956 (1931).

The sensitivity and accuracy possible with the Szivessy compensator are summarized below for different values of η.

η	δ	Accuracy
$10^{-1}\cdot 2\pi$	$3\times10^{-2}\cdot 2\pi$–$5\times10^{-3}\cdot 2\pi$	—
$10^{-2}\cdot 2\pi$	$1\times10^{-3}\cdot 2\pi$–$1\times10^{-4}\cdot 2\pi$	0.2–0.3%
$5\times10^{-3}\cdot 2\pi$	$5\times10^{-5}\cdot 2\pi$–$3\times10^{-5}\cdot 2\pi$	1%

The 'Modified' Szivessy and Brace Compensators[24]

The phase difference measurable with the original Brace and Szivessy compensators is limited in range by the fixed constants of the instruments. The range of the Brace compensator is governed by Eq. (37) *viz.*

$$|\tan(\delta+\eta/2)| \leqslant |\tan\kappa|,$$

whereas Eq. (56) *viz.*

$$|\tan\delta| \leqslant |\tan\eta/2|$$

decides the range of the Szivessy compensator.

It is possible, however, to use both instruments so that any phase difference can be measured without restriction, but they are then applicable only to the measurement of phase differences; they cannot be used to measure the azimuth and ellipticity of an elliptically polarized radiation.

I. The "Modified" Szivessy Compensator

The components of this instrument are identical with those of the Szivessy 'simple half-shade' of the last section—the mica half-shadow plate producing a phase difference of about $\pi/2$. The analyzer however is provided with a divided circle and vernier to enable its azimuth to be read to within half a minute; the polarizer has a crude dividing circle serving only to reset the instrument should repetition of results be required.

The essential characteristic of this instrument, in contra-distinction to the original Szivessy, is that the unknown phase difference is found by a determination of the analyzer azimuth when half-shadow conditions are realized: the azimuth of

[24] G. Szivessy and W. Herzog, Zeits. f. Instrumentenk. **57**, 305 (1937).

the half-shadow plate remains fixed. It is, therefore, found preferable to measure azimuths, not with respect to either the polarizer or analyzer azimuth, but from the azimuth of the plate D under examination. Figure 12 shows the parameters etc., used throughout this section.

Theory. For the moment let us consider both arrangements A and B (Fig. 12). If J_2 and J_1 are the intensities of the field of view covered and not covered by the half-shadow plate then, for arrangement A, from Eqs. (4) and (5), putting

$$\varphi=(\alpha-\beta),\quad \gamma_1=(\epsilon-\beta),\quad \gamma_2=-\beta;\quad \delta_1=\eta,\quad \delta_2=\delta,$$

we obtain

$$J_2-J_1=-\sin 2(\beta-\epsilon)\times\sin\eta/2\{\sin 2\alpha(\cos 2\epsilon\,\sin\eta/2\,\cos\delta+\cos\eta/2\,\sin\delta)-\cos 2\alpha\,\sin 2\epsilon\,\sin\eta/2\},\quad (59)$$

which is zero if one of the following conditions holds

(a) $\sin 2(\beta-\epsilon)=0$, satisfied by

$$\beta=\epsilon \quad \text{or} \quad \epsilon\mp\pi/2, \quad (60a)$$

(b) $\sin\eta/2=0$, one solution being $\eta=2\pi$, (60b)

or if the analyzer azimuth $\bar{\alpha}$ satisfies

$$\cos 2\epsilon\,\cos\delta+\sin\delta\,\cot\eta/2-\sin 2\epsilon\,\cot 2\bar{\alpha}=0. \quad (60c)$$

Identical conditions hold for arrangement B if the polarizer and analyzer azimuths are interchanged.

The essential half-shadow condition is given by Eq. (60c) in which the analyzer azimuth $\bar{\alpha}$ is always real; there are no limits imposed on the range of measurement of the phase difference. We see also that Eq. (60c) is independent of the polarizer azimuth β and similarly arrangement B is independent of the analyzer azimuth α. For this reason arrangement A is preferred since it is easier in practice to rotate the analyzer than the polarizer. We shall not consider arrangement B further.

If $\cot 2\bar{\alpha}$ is positive, the solution of Eq. (60c) takes the form $\bar{\alpha}=\bar{\alpha}_0\pm(n\pi/2)$ $(n=0,\ 1,\ 2,\ \cdots)$, and assuming the limits $-\pi/2\leqslant\bar{\alpha}_0\leqslant+\pi/2$, the roots are two in number, i.e.,

$$\bar{\alpha}_1=\bar{\alpha}_0(\bar{\alpha}_1>0) \quad \text{and} \quad \bar{\alpha}_2=\bar{\alpha}_0-\pi/2(\bar{\alpha}_2<0). \quad (61)$$

If $\cot 2\bar{\alpha}$ is negative within the same limits we get two further roots:

$$\bar{\alpha}_3=-\bar{\alpha}_2=\pi/2-\bar{\alpha}_0(\bar{\alpha}_3>0)$$

and

$$\bar{\alpha}_4=-\bar{\alpha}_1=-\bar{\alpha}_0(\bar{\alpha}_4<0). \quad (62)$$

If these azimuths correspond to the drum readings p_1, p_2, p_3, and p_4, then

$$2\bar{\alpha}_0=p_1-p_4=\pi-(p_3-p_2). \quad (63)$$

When ϵ, $\bar{\alpha}$, and η are known it is possible to solve Eq. (60c) directly, but unless the limits of δ are known the requisite value cannot be chosen with certainty from the two obtained.

Suppose, however, ϵ is first given any value $\epsilon_1(\neq\pm\pi/4)$ and then a value $\epsilon_1-\pi/2$ if ϵ_1 is positive, or $\epsilon_1+\pi/2$ if ϵ_1 is negative.

If $\bar{\alpha}_{01}$ and $\bar{\alpha}_{02}$ are the analyzer half-shadow azimuths then from Eq. (60c)

$$\cos 2\epsilon_1\,\cos\delta+\sin\delta\,\cot\eta/2-\sin 2\epsilon_1\,\cot 2\bar{\alpha}_{01}=0,$$

and

$$-\cos 2\epsilon_1\,\cos\delta+\sin\delta\,\cot\eta/2+\sin 2\epsilon_1\,\cot 2\bar{\alpha}_{02}=0,$$

from which we obtain

$$2\,\sin\delta=\sin 2\epsilon_1(\cot 2\bar{\alpha}_{01}-\cot 2\bar{\alpha}_{02})\,\tan\eta/2, \quad (64a)$$

and

$$2\,\cos\delta=\tan 2\epsilon_1(\cot 2\bar{\alpha}_{01}+\cot 2\bar{\alpha}_{02}). \quad (64b)$$

These equations determine δ uniquely.[25]

Further simplification is achieved if $\epsilon_1=\pm\pi/4$, whence

$$\sin\delta=\pm\cot 2\bar{\alpha}\,\tan\eta/2 \quad (0\leqslant\delta\leqslant 2\pi), \quad (65)$$

the positive sign holding for $\epsilon_1=+\pi/4$, the negative for $\epsilon_1=-\pi/4$.

Let us now consider the half-shadow sensitivity possible when using the instrument to satisfy Eq. (65). With Eqs. (11), (59) and the expression for J_0 the half-shadow sensitivity s is given by

$$s=\frac{4\,\cos 2\beta\,\sin\eta/2(\sin 2\bar{\alpha}\,\sin\eta/2\pm\cos 2\bar{\alpha}\,\cos\eta/2\,\sin\delta)}{1+\cos 2\bar{\alpha}\,\cos 2\beta+\sin 2\bar{\alpha}\,\sin 2\beta\,\cos\delta}, \quad (66)$$

[25] Note that a value for η can be found without recourse to an independent measurement, for

$$\tan^2\eta/2=\frac{4-\tan^2 2\epsilon_1(\cot 2\bar{\alpha}_{01}+\cot 2\bar{\alpha}_{02})^2}{\sin^2 2\epsilon_1(\cot 2\bar{\alpha}_{01}-\cot 2\bar{\alpha}_{02})^2};$$

W. Herzog, Zeits. f. Physik **97**, 225 (1935).

where the positive or negative sign holds if $\epsilon = +\pi/4$ or $-\pi/4$, respectively. For given values of η and $\bar{\alpha}$, maximum sensitivity occurs for a polarizer azimuth, β_m, satisfying the equation $\partial s/\partial\beta = 0$, i.e.,

$$\sin 2\beta_m = -\sin 2\bar{\alpha}\cos\delta. \tag{67}$$

Within the prescribed limits $-\pi/2 \leqslant \beta_m \leqslant +\pi/2$, this gives two azimuths $\beta_{01} = \beta_m$, $\beta_{02} = \pm\pi/2 - \beta_m$, and for an analyzer azimuth $\bar{\alpha}$ one corresponds to a maximum, the other to a minimum: they change their roles for the second azimuth $\bar{\alpha} - \pi/2$. Hence

$$s_{\max} = 4\frac{\tan\eta/2}{|\sin\delta|}(\sin^2\eta/2 - \sin^2\delta\cos^2\eta/2), \tag{68}$$

which is greater the nearer η is to $2n\pi$ and δ to $n\pi$ ($n = 0, 1, 2, \cdots$). The value $\eta = 2\pi$ is a root of Eq. (60b) and is, therefore, unsuitable as are values near π because $\sin\delta$ is then indeterminate from Eq. (65). In most cases a value near $\pi/2$ gives sufficient half-shadow sensitivity.

Method of Use. We are now in the position to formulate the procedure for the determination of δ. Initially the half-shadow plate H and doubly refracting plate D are set in their extinction azimuths (i.e., $\beta = \epsilon = 0$ or $\beta = 0$, $\epsilon = \pi/2$, respectively) between crossed polarizer and analyzer. Let the drum reading for the analyzer be p_0. Then, by rotation of H in the appropriate direction, ϵ is given the value $+\pi/4$; by rotation of the analyzer in the positive sense a provisional half-shadow position is obtained.

The polarizer is now set in the azimuth β_m given by Eq. (67). This position is found experimentally by using the fact that a very small departure from the provisional half-shadow azimuth found previously brings about a marked intensity difference in both halves of the field of view. The polarizer is rotated until this condition occurs. The analyzer is finally adjusted to azimuth $\bar{\alpha}$-corresponding to a drum reading of p_1. By rotating the analyzer through $\pi/2$ in the negative sense and the polarizer through $\pm\pi/2$, the drum reading p_2 corresponding to the azimuth $\bar{\alpha} - \pi/2$ is obtained. This entire procedure is repeated for $\epsilon = -\pi/4$, the drum readings being p_3 and p_4, respectively. Then from Eqs. (63) and (65)

$$\begin{aligned}\sin\delta &= \cot[+(p_1 - p_4)]\tan\eta/2 \\ &= -\cot[+(p_3 - p_2)]\tan\eta/2 \quad (0 \leqslant \delta \leqslant 2\pi),\end{aligned} \tag{69}$$

from which δ can be determined. This adjustment is deemed correct if

$$\begin{aligned}&+(p_1 - p_0) = +(p_2 - p_0) + \pi/2, \\ \text{and} \qquad &+(p_3 - p_0) = +(p_4 - p_0) + \pi/2.\end{aligned} \tag{70}$$

Under these conditions, according to Szivessy and Herzog, the lower limit of the compensator varies from $3\times10^{-5}\cdot 2\pi$ to $2\times10^{-5}\cdot 2\pi$ depending upon the value chosen for η.

II. The "Modified" Brace Compensator

In this instrument we have (compare the unmodified Brace compensator) two possible arrangements A and B (Fig. 13), but now, in seeking the half-shadow positions, the analyzer azimuth is varied and not the compensator-plate azimuth. The analyzer is provided with a divided circle and vernier to enable its azimuth to be read to within half a minute; the remaining components are also provided with divided circles but of a more coarse graduation. The phase difference κ of the compensator plate must be very accurately known and is chosen to be as

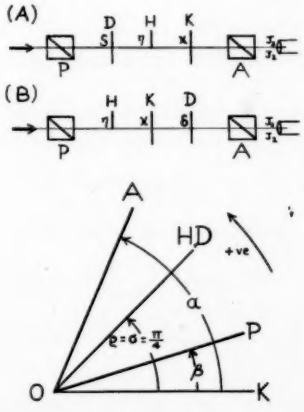

FIG. 13. The optical arrangements A and B and azimuths of the directions of vibration for the modified Brace compensator. P, polarizer; A, analyzer; D, plate under test; H, half-shadow plate; K, compensator plate; OP, OA, OD, OH, OK, their respective vibration directions. δ, η, κ, are the phase differences produced by D, H, and K, respectively. The azimuths α, β, σ, and ρ of OA, OP, OD, and OH, respectively, are measured from OK.

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small as possible. The phase difference η produced by the half-shadow plate may or may not be known according to the method of use. The values for κ and η will be discussed in the following paragraphs.

The azimuths are again not measured with respect to the vibration directions of either the polarizer or analyzer but from the main vibration direction of the faster ray in the compensator plate. Figure 13 shows the nomenclature used.

Theory. For arrangement *A*, with the usual notation, from Eq. (3) putting $\varphi=\alpha-\beta$, $\gamma_1=\gamma_2=\pm\pi/4-\beta$ (*OH* and *OD* parallel) or $\gamma_1=\gamma_2\mp\pi/2$ (*OH* and *OD* perpendicular),

$$J_3=\cos^2(\alpha-\beta)-\cos2\alpha\cos2\beta\sin^2[(\delta\pm\eta)/2]-\sin2\alpha\sin2\beta\sin^2\kappa/2\pm\tfrac{1}{2}\sin2\alpha\cos2\beta\sin(\delta\pm\eta)\sin\kappa, \quad (71)$$

and from Eq. (4)

$$J_2=\cos^2(\alpha-\beta)-\cos2\alpha\cos2\beta\sin^2\delta/2-\sin2\alpha\sin2\beta\sin^2\kappa/2\pm\tfrac{1}{2}\sin2\alpha\cos2\beta\sin\delta\sin\kappa. \quad (72)$$

The difference in intensity then becomes

$$J_3-J_2=\mp\cos2\beta\sin\eta/2\{\cos2\alpha\sin(\delta\pm\eta/2)\mp\sin2\alpha\sin\kappa\cos(\delta\pm\eta/2)\}, \quad (73)$$

which is zero if any of the following conditions hold;

(a) $\cos2\beta=0$, satisfied by $\beta=\pm\pi/4$, (74a)

(b) $\sin\eta/2=0$, one solution then being $\eta=2\pi$, (74b)

or if the analyzer azimuth $\bar{\alpha}$ satisfies

$$\cot2\bar{\alpha}=\pm\sin\kappa\cot(\delta\pm\eta/2). \quad (74c)$$

In Eqs. (71)–(73) and (74c), the upper or lower sign for η holds if $\gamma_1=\gamma_2$ or $\gamma_1=\gamma_2\mp\pi/2$, respectively, and where the double sign again occurs the upper or lower sign holds if $\sigma=+\pi/4$ or $-\pi/4$, respectively.

Similarly, by putting

$$\phi=\alpha-\beta, \quad \gamma_1=\gamma_3=\pm\pi/4-\beta$$

(*OH* and *OD* parallel) [or $\gamma_1=\gamma_3\mp\pi/2$ (*OH* and *OD* perpendicular)], $\gamma_2=-\beta$ in Eq. (3) for arrangement *B*, we obtain

$$J_3-J_2=\mp\cos2\beta\sin\eta/2\times\{\cos2\alpha(\sin\delta\cos\kappa\cos\eta/2\pm\cos\delta\sin\eta/2)\mp\sin2\alpha\sin\kappa\cos\eta/2\}, \quad (75)$$

which again is zero if (a) $\cos2\beta=0$, (b) $\sin\eta/2=0$ [(76a), (76b)] and the analyzer azimuth $\bar{\alpha}$ satisfies

$$\cot2\bar{\alpha}=\pm\sin\kappa/(\sin\delta\cos\kappa\pm\cos\delta\tan\eta/2). \quad (76c)$$

In Eqs. (75), (76c), the upper or lower sign to be attached to the factor containing $\sin\eta/2$ or $\tan\eta/2$ holds if $\gamma_1=\gamma_3$ or $\gamma_1=\gamma_3\mp\pi/2$, respectively, and to the factor containing $\sin\kappa$ if $\sigma=+\pi/4$ or $-\pi/4$, respectively.

The essential half-shadow conditions are given by Eqs. (74c) and (76c) in which the analyzer azimuths are always real and independent of the polarizer azimuths.

The roots of these equations have already been discussed in connection with the modified Szivessy compensator and it is sufficient to say that Eqs. (61) and (62) hold.

For arrangement *A*, solving Eq. (74c) for δ we get (with $\gamma_1=\gamma_2$)

$$\tan\delta=\frac{\pm\sin\kappa\tan2\bar{\alpha}-\tan\eta/2}{1\pm\sin\kappa\tan2\bar{\alpha}\tan\eta/2} \quad (0\leqslant\delta\leqslant2\pi), \quad (77)$$

where the upper sign holds for $\sigma=+\pi/4$, the lower for $\sigma=-\pi/4$. With $\gamma_1=\gamma_2\pm\pi/2$ the factors containing $\tan\eta/2$ change their sign. For arrangement *B* from Eq. (76c) (with $\gamma_1=\gamma_3$)

$$\tan\delta=\frac{-\cos\kappa\sin\eta/2\cos^2\!2\bar{\alpha}\pm\sin\kappa\sin2\bar{\alpha}(\cos^2\!2\bar{\alpha}-\sin^2\!\kappa\cos^2\eta/2)^{\frac{1}{2}}}{\cos\eta/2(\cos^2\!2\bar{\alpha}-\sin^2\!\kappa)}, \quad (0\leqslant\delta\leqslant2\pi), \quad (78)$$

and if $\gamma_1=\gamma_3\pm\pi/2$ the first term in the numerator changes sign.

There are two solutions of Eqs. (77) and (78) and it is possible to choose the correct one with certainty only if the limits of δ are known.

There are alternative methods of measurement

which may be considered. Suppose in arrangement A the plate D is removed, then the analyzer azimuth $\bar{\alpha}_0$ in the half-shadow position satisfies [from Eq. (74c)]

$$\cot 2\bar{\alpha}_0 = \pm \sin\kappa \cot \pm\eta/2, \tag{79}$$

whence, eliminating η from Eqs. (74c) and (79),

$$\tan\delta = \pm \sin\kappa \frac{\tan 2\bar{\alpha} - \tan 2\bar{\alpha}_0}{1 + \tan 2\bar{\alpha}_0 \tan 2\bar{\alpha} \sin^2\kappa} \qquad (0 \leqslant \delta \leqslant 2\pi), \tag{80}$$

the upper sign holding for $\sigma = +\pi/4$, the lower for $\sigma = -\pi/4$. Again, unfortunately δ cannot be uniquely determined.

In arrangement B suppose H is rotated through $\pm\pi/2$ from azimuth $\pi/4$, i.e., say from $\gamma_1 = \gamma_3$ to $\gamma_1 = \gamma_3 \pm \pi/2$, then if $\bar{\alpha}_{01}$ and $\bar{\alpha}_{02}$ are the corresponding half-shadow azimuths from Eq. (76c)

$$\left.\begin{aligned} &\cos\kappa \sin\delta \pm \tan\eta/2 \cos\delta \\ &\qquad \mp \sin\kappa \tan 2\bar{\alpha}_{01} = 0 \end{aligned}\right\} \gamma_1 = \gamma_3,$$

$$\left.\begin{aligned} &\cos\kappa \sin\delta \mp \tan\eta/2 \cos\delta \\ &\qquad \mp \sin\kappa \tan 2\bar{\alpha}_{02} = 0 \end{aligned}\right\} \gamma_1 = \gamma_3 \pm \pi/2,$$

subtracting

$$2\cos\delta = \pm \sin\kappa \cot\eta/2 (\tan 2\bar{\alpha}_{01} - \tan 2\bar{\alpha}_{02}), \tag{81}$$

adding

$$2\sin\delta = \pm \tan\kappa (\tan 2\bar{\alpha}_{01} + \tan 2\bar{\alpha}_{02}). \tag{82}$$

In these equations the positive value holds if $\sigma = +\pi/4$, the negative if $\sigma = -\pi/4$. δ can, then, be calculated from Eq. (82), two cases being considered: (a) the limits of δ known but η unknown, (b) the limits of δ unknown and η known—in this case the limits of δ can be found from Eq. (81). This shows, therefore, that this method of use for the modified Brace is by far the most complete.

Let us consider now whether it is better for the main vibration directions of the faster components of the plates H and D to lie parallel or perpendicular to each other. For arrangement A the error $d\delta$ in δ, due to an error $d\bar{\alpha}$ in $\bar{\alpha}$, is given by differentiation of Eq. (74c), i.e.,

$$\sec^2(\delta \pm \eta/2) d\delta = \pm 2 \sin\kappa \sec^2 2\bar{\alpha} \cdot d\bar{\alpha},$$

from which it is clear that $d\delta$ is greater for a given error $d\bar{\alpha}$ the greater the value of $\cos^2(\delta \pm \eta/2)$. The positive sign holds if the vibration directions are parallel, the negative if they are perpendicular. A simple expansion shows that for greatest accuracy, if $\sin 2\delta \sin\eta$ is positive, the directions must be parallel, if negative they must be perpendicular.

Similarly for arrangement B by differentiation of Eq. (76c) we get

$$(\cos\kappa \cos\delta \mp \tan\eta/2 \sin\delta) d\delta = \pm 2 \sin\kappa \sec^2 2\bar{\alpha} \cdot d\bar{\alpha},$$

which means that for a given value of $d\bar{\alpha}$, $d\delta$ is greater the smaller is $(\cos\kappa \cos\delta \mp \tan\eta/2 \sin\delta)$. The upper or lower sign holds according as the directions are parallel or perpendicular, respectively, and therefore the plates must lie parallel if the expression $\sin 2\delta \cos\kappa \tan\eta/2$ is negative and perpendicular if it is positive. If the last mentioned method of using arrangement B is used then, of course, these last remarks are not applicable.

Although the analyzer half-shadow azimuth is independent of the polarizer azimuth, the latter has a definite value for maximum half-shadow sensitivity. From Eqs. (11), (73), and (74c) the half-shadow sensitivity (s_A) for arrangement A is given by

$$s_A = |M_A| |N_A|, \tag{83}$$

where

$$M_A = \cos 2\beta / [1 + (\cos 2\bar{\alpha} \cos\delta \pm \sin 2\bar{\alpha} \sin\delta \sin\kappa) \cos 2\beta + \sin 2\bar{\alpha} \cos\kappa \sin 2\beta],$$

$$N_A = 4 \sin\eta/2 \{\sin 2\bar{\alpha} \sin(\delta \pm \eta/2) \pm \cos 2\bar{\alpha} \sin\kappa \cos(\delta \pm \eta/2)\}.$$

The positive sign or negative sign for $\eta/2$ holds if OH and OD are parallel or perpendicular, respectively. For all other factors the upper or lower signs hold if $\sigma = +\pi/4$ or $-\pi/4$, respectively.

Similarly for arrangement B from Eqs. (11), (75), and (76c)

$$s_B = |M_B| |N_B|, \tag{84}$$

where

$$M_B = \cos 2\beta / [1 + \cos 2\bar{\alpha} (\cos\delta \pm \sin\delta \sin\kappa) \cos 2\beta + \sin 2\bar{\alpha} \cos\kappa \sin 2\beta],$$

$$N_B = 4 \sin\eta/2 \{\sin 2\bar{\alpha} (\sin\delta \cos\kappa \cos\eta/2 \pm \cos\delta \sin\eta/2) \pm \cos 2\bar{\alpha} \sin\kappa \cos\eta/2\}.$$

In the expression for N_B we use $+\cos\delta \sin\eta/2$ if OH and OD are parallel, $-\cos\delta \sin\eta/2$ if they are perpendicular. The upper or lower signs hold in the remaining factors if $\sigma=+\pi/4$ or $-\pi/4$, respectively.

Since the polarizer azimuth occurs only in M_A and M_B, maximum sensitivity is obtained with polarizer azimuths satisfying the equations $\partial M_A/\partial\beta=0$ and $\partial M_B/\partial\beta=0$, respectively, i.e.,

$$\sin 2\beta_m = -\sin 2\bar{\alpha} \cos\kappa, \tag{85}$$

where $\bar{\alpha}$ is given by Eq. (74c) for A and by Eq. (76c) for B. The solutions to this equation have already been discussed in detail [see Eqs. (46)].

With the polarizer in the most favorable azimuth the half-shadow sensitivity for arrangement A is now given by

$$s_A = 4(\tan\eta/2/|\sin\kappa|) \times\{\sin^2(\delta\pm\eta/2)+\sin^2\kappa\cos^2(\delta\pm\eta/2)\}, \tag{86}$$

where the upper or lower sign holds if OH and OD are parallel or perpendicular, respectively.

This shows s_A to be greater the nearer κ is to 0, π, or 2π, and the smaller the deviation of η from 2π. The limiting case $\eta=2\pi$ is rejected because it is a solution of Eq. (74b). A suitable half-shadow sensitivity is obtained if η is chosen between $3\pi/2$ and 2π, and κ is sufficiently small (*ca.* $1\times10^{-2}\cdot2\pi$). If η is in the neighborhood of 2π, s_A is greater the smaller the deviation of δ from $\pi/2$ or $3\pi/2$, respectively. Arrangement A is, then, especially suitable for measurements of this order of magnitude.

For arrangement B, using Eqs. (84) and (85),

$$s_B = 4\frac{\sin\eta/2}{|\sin\kappa|}\cdot\frac{(\sin\delta\cos\kappa\cos\eta/2\pm\cos\delta\sin\eta/2)^2+\sin^2\kappa\cos^2\eta/2}{(\cos\delta\pm\sin\delta\sin\kappa)\cos\eta/2+[\cos^2\eta/2+(\sin\delta\cos\kappa\cos\eta/2\pm\cos\delta\sin\eta/2)^2]^{\frac{1}{2}}}.$$

In the denominator $+\sin\delta\sin\kappa$ is used if $\sigma=+\pi/4$, $-\sin\delta\sin\kappa$ if $\sigma=-\pi/4$. Where $\sin\eta/2$ appears, the upper or lower sign is used according to whether OH is parallel or perpendicular to OD.

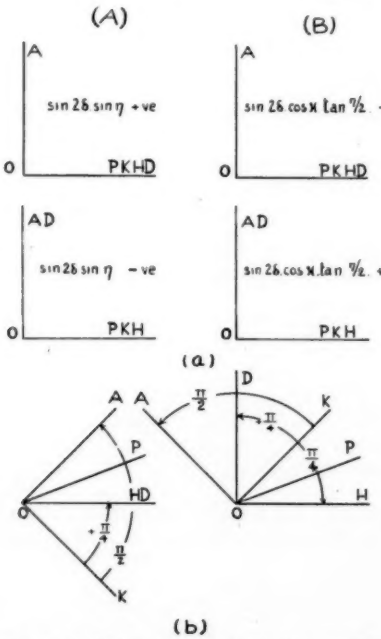


FIG. 14. Initial orientation for the modified Brace compensator. (a). The extinction azimuths for arrangements A and B. (b). Initial azimuths before seeking half-shadow condition.

This shows s_B to be greater the nearer κ is to O, π or 2π and the smaller the deviation of η from π. With $\eta=\pi$ and κ about $1\times10^{-2}\cdot2\pi$, s_B is greater the smaller the deviation of δ from O, π or 2π. Arrangement B is, therefore, especially suitable for measurements of very small phase differences.

Method of Use. Before a determination of an unknown phase difference is carried out the main vibration directions of the plates D, H, and K are found, the plates are then placed between crossed polarizer and analyzer so that they are in the extinction azimuths. Figure 14(a) shows these positions which necessitates a provisional determination of δ.[26]

To measure the analyzer half-shadow azimuth $\bar{\alpha}$, K is suitably rotated by $\pi/4$ so that $\sigma=+\pi/4$, P is rotated so that it does not coincide with H, and A suitably rotated by $\pm\pi/4$ so that its vibration direction is perpendicular to that of K (Fig. 14b).

The procedure now is the same as that in the modified Szivessy, two sets of readings for the analyzer azimuth being obtained with $\sigma=+\pi/4$

[26] If, in arrangement B, Eq. (82) is to be used for the calculation of δ, then it is immaterial whether OD and OH are parallel or perpendicular whatever the sign of $\sin 2\delta\cos\kappa\tan\eta/2$.

or $-\pi/4$, respectively. δ may now be calculated from Eqs. (77) or (78), respectively. If, however, for arrangement A, Eq. (80) is used, a repetition of the above procedure with D removed gives $\bar{\alpha}_0$, whereas if for arrangement B Eq. (82) is used, H must be rotated through $\pm\pi/2$ to get a second set of readings. The criterion for correct adjustment is given by Eqs. (70).

It should be noted that, if, in arrangement A, the sequence of the plates is K, H, D, or K, D, H, and in arrangement B the plate sequence is D, K, H, then Eqs. (73) and (75) hold, respectively, if $\bar{\alpha}$ is replaced by $\bar{\beta}$ and *vice versa*, i.e., the polarizer and analyzer change their roles.

The lower limit of the phase differences measurable by the modified Brace compensator varies from $3\times10^{-5}\cdot2\pi$ to $2\times10^{-5}\cdot2\pi$.

The Sénarmont or Quarter-Wave Plate Compensator[27]

The Sénarmont compensator (Fig. 15) consists essentially of a mica or quartz $\lambda/4$ plate, corresponding to the frequency of the light used, and an analyzer. According to the type of the analyzer it may be classed as a one- or two-plate compensator. The elliptically polarized light under examination, and having a phase difference δ, is arranged to fall on the $\lambda/4$ plate orientated in azimuth 0 or $\pi/2$; it is converted into linearly polarized light. In general the light will be rotated by a definite angle with respect to the incident direction and the analyzer serves to measure this angle of rotation. For this purpose it is provided with a divided circle and vernier. Usually there is a half-shadow device to obtain increased sensitivity—the Schönrock[28] prism and the Chauvin[29] analyzer being most often used; in either case the dividing line of the two halves of the field of view is rotated in seeking the half-shadow position.

[27] H. de Sénarmont, Ann. Chim. Phys. **73**, 337 (1840); F. Gabler and P. Sokob, Zeits. f. Instrumentenk. **58**, 301 (1938); F. Gabler and P. Sokob, Zeits. f. Instrumentenk. **61**, 298 (1941); F. Gabler and P. Sokob, Physik. Zeits. **42**, 319 (1941).

[28] A symmetrical prism with right end faces, consisting of two Glan-Thomson prisms cemented together so that the vibration directions make a small angle 2ϵ with each other. O. Schönrock, *Handbuch der Physik* **19**, 750 (1928).

[29] A polarizing prism combined with a $\lambda/2$ plate covering half the field of view. The vibration directions make an angle ϵ with each other; this angle can be varied. M. Chauvin, J. de Phys. **9**, 21 (1890); Ann. de Toulouse **3**(J) 28, (1889).

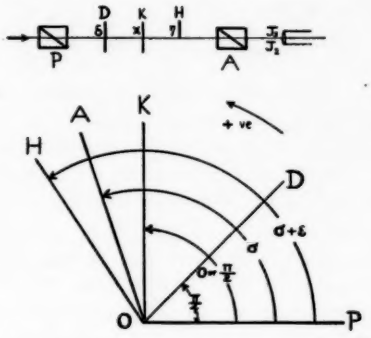


FIG. 15. The optical system and azimuths of the directions of vibration for the Sénarmont compensator with half-shadow. P, polarizer; A, analyzer; D, plate under test; H, half-shadow plate; K, compensator plate; OP, OA, OD, OH, and OK, their respective vibration directions. δ, η, and κ are the phase differences produced by D, H, and K, respectively. σ is the azimuth of the dividing line, ϵ the angle between the vibration directions.

With the arrangement shown in Fig. 15 for the measurement of δ, it can be shown that if the azimuth of D is $\pm\pi/4$ light will emerge from the $\lambda/4$ plate linearly polarized for any value of δ when the azimuth of K is 0 or $\pi/2$.[30]

Theory. I. *Simple polarization prism as analyzer.* If a simple polarization prism is used as analyzer then, for only plate K in azimuth 0 or $\pi/2$, the intensity of the field of view is zero for crossed polarizer and analyzer, i.e., the analyzer azimuth ϕ_0 satisfies

$$\phi_0=\pm\pi/2 \tag{88}$$

corresponding to a drum reading p_0. With plates D and K in position by substituting in Eq. (4) the conditions

$$\gamma_1=+\pi/4,\quad \gamma_2=0 \text{ or } \pi/2;\quad \delta_1=\delta,\quad \delta_2=\pi/2, \tag{89}$$

we find

$$J_2=\cos^2\varphi-\cos2\varphi\,\sin^2\delta/2 \pm\sin2\varphi\,\sin\delta/2\,\cos\delta/2, \tag{90}$$

or

$$J_2=\cos^2(\varphi\mp\delta/2), \tag{90a}$$

which is zero for an analyzer azimuth ϕ_1 given by

$$\varphi_1=\pm\pi/2\pm\delta/2. \tag{91}$$

In Eqs. (90), (90a), and (91) the upper sign of δ holds if $\gamma_2=0$, the lower if $\gamma_2=\pi/2$. If the azimuth ϕ_1 corresponds to a drum reading p_1,

[30] For a full discussion see F. Gabler and P. Sokob, Zeits f. Instrumentenk. **58**, 301 (1938) (see reference 27).

it therefore follows that

$$\varphi_1-\varphi_0=\pm\delta/2, \tag{92}$$

and the value $2(p_1-p_0)$ corresponds to the unknown phase difference $\pm\delta$. The sign of δ is most simply determined by interchanging D with a doubly refracting plate of known sign, e.g., an optical flat subjected to stress.

II. *Half-shadow analyzers.* Let us consider now the use of a Schönrock prism as analyzer. The direction of the dividing line of the two halves of the field of view is taken as the azimuth denoted by σ; the planes of polarization then have azimuths $\sigma\pm\epsilon$.

If now J_2' and J_2'' are the intensities of the two halves of the field of view, then by Eq. (4) ($\gamma_1=\pi/4$, $\gamma_2=0$ or $\pi/2$, $\delta_1=\delta$, $\delta_2=\pi/2$, $\varphi=\sigma\pm\epsilon$)

$$J_2'=\cos^2(\sigma+\epsilon)-\cos2(\sigma+\epsilon)\sin^2\delta/2 \pm\sin2(\sigma+\epsilon)\sin\delta/2\cos\delta/2, \tag{93}$$

$$J_2''=\cos^2(\sigma-\epsilon)-\cos2(\sigma-\epsilon)\sin^2\delta/2 \pm\sin2(\sigma-\epsilon)\sin\delta/2\cos\delta/2. \tag{94}$$

For the half-shadow position ($J_2'=J_2''$) the azimuth $\bar\sigma$ satisfies

$$\tan2\bar\sigma=\pm\tan\delta, \tag{95}$$

i.e.,

$$\bar\sigma=\pm\pi/2\pm\delta/2,$$

where the upper sign holds for $\gamma_2=0$, the lower for $\gamma_2=\pi/2$. If σ_0 is the corresponding azimuth with plate D removed, $\sigma_0=\pm\pi/2$ and

$$\therefore\quad \bar\sigma-\sigma_0=\pm\delta/2. \tag{97}$$

When using the Chauvin analyzer we have, in effect, a three-plate compensator. The analyzer azimuth is again denoted by the direction of the dividing line of the two halves of the field of view. The intensity, J_2, of the part of the field uncovered by the half-shadow plate, is given by Eq. (90) and that of the remaining half (J_3) is found from Eq. (3) ($\gamma_1=\pi/4$, $\gamma_2=0$ or $\pi/2$, $\gamma_3=\sigma+\epsilon$ ($\epsilon<\pi/2$); $\varphi=\sigma$; $\delta_1=\delta$, $\delta_2=\pi/2$, $\delta_3=\pi$),

$$J_3=\cos^2\sigma-\cos2\sigma\sin^2\delta/2 -\sin2\sigma\sin\delta/2\cos\delta/2 -\sin2(\sigma+\epsilon)\sin2\epsilon\cos\delta -\cos2(\sigma+\epsilon)\sin2\epsilon\sin\delta. \tag{98}$$

For a balance ($J_3=J_2$),

(a) $\sin2\epsilon=0$, i.e., $\epsilon=0$ or $\pi/2$.

(b) $\tan2(\bar\sigma+\epsilon)=\pm\tan\delta,$ (99)

i.e.,

$$\bar\sigma+\epsilon=\pm\pi/2\pm\delta/2, \tag{100}$$

where the upper sign holds if $\gamma_2=0$, the lower if $\gamma_2=\pi/2$, and again if σ_0 is the half-shadow azimuth without the plate D in position then

$$\bar\sigma-\sigma_0=\pm\delta/2. \tag{101}$$

A comparison of Eqs. (92), (97), and (101) shows them to be identical in form, and so when using a Schönrock prism or Chauvin analyzer the adjustment is made to a half-shadow position, whereas with a simple analyzer the adjustment is made to darkness.

In practice it is somewhat difficult to fulfill precisely the conditions expressed by Eqs. (89), and in the Chauvin analyzer the phase difference of the $\lambda/2$ plate may differ slightly from π. We may reasonably have the conditions

$$\gamma_1=\pi/4+\Delta\gamma_1,\quad \gamma_2=\pi/2+\Delta\gamma_2;\qquad \delta_1=\delta,\quad \delta_2=\pi/2+\Delta\delta_2,\quad \delta_3=\pi+\Delta\delta_3, \tag{102}$$

where $\Delta\gamma_1$, $\Delta\gamma_2$, $\Delta\delta_2$, and $\Delta\delta_3$ are the departures from the ideal. In this case, the light emerging from the plate K will be elliptically polarized and instead of the simple Eqs. (92), (97), and (101) we have most complicated expressions.[31] Examination of these, however, shows that the small deviations affect only slightly the half-shadow analyzer azimuth and produce only second-order errors in δ. Two cases which are realizable in practice to a good approximation may be mentioned, namely, (a) $\Delta\gamma_1=\Delta\gamma_2=\Delta\delta_2=0$ and $\Delta\delta_3$ arbitrary in which case the general equation $\sigma_1-\sigma_0=\pm\delta/2$ holds, and (b) $\Delta\delta_2\neq0$; Eq. (95) is then replaced by

$$\tan2\sigma'=\pm\cos\Delta\delta_2\tan\delta. \tag{103}$$

Another factor which may possibly influence the accuracy is the effect of multiple reflections at the bounding surfaces, which in the main cause an alteration in the phase differences normally produced by the plates. It is possible to treat these mathematically[32] and to this purpose Eq. (3) can be replaced by an equation including the effect of the reflections.[32a] The treatment is then identical with that given above.

[31] F. Gabler and P. Sokob, Zeits. f. Instrumentenk. **58**, 301 (1938).

[32] F. Gabler and P. Sokob, Zeits. f. Physik **116**, 47 (1940).

[32a] Reference 32, Eq. 22.

For a Schönrock analyzer instead of Eq. (95), for $\gamma_2=0$ we obtain

$$\tan 2\sigma_1=\frac{\cos\Delta\chi_2\sin\delta}{x+y\cos\delta}, \qquad (104)$$

and with $\gamma_2=\pi/2$

$$\tan 2\sigma_2=\frac{\cos\Delta\chi_2\sin\delta}{x-y\cos\delta}, \qquad (105)$$

where $\Delta\chi_2$ is the deviation from $\pi/2$ of the compensator plate K, and x and y are quantities dependent on the reflection coefficients. x is always small, y and $\Delta\chi_2$ are instrumental constants which can be determined. If $y\cong 1$, as is often the case, we find

$$\tan(\sigma_1-\sigma_2)\cong\cos\Delta\chi_2\tan\delta \quad \text{(cf. Eq. 103)} \qquad (106)$$

and, further, if $\Delta\chi_2=0$

$$\tan(\sigma_1-\sigma_2)=\tan\delta \quad \text{(cf. Eq. 95)}. \qquad (106a)$$

Similar results hold for the Chauvin analyzer so that δ can be found by using the formula derived without taking the reflections into account, provided the mean of two half-shadow azimuths obtained by having $\gamma_2=0$ and $\gamma_2=\pi/2$ is used instead of a single azimuth.

Finally, let us consider the half-shadow sensitivity. Using a Schönrock prism from Eqs. (11), (93), (94), and (95) we find

$$s=\mp 2\frac{\sin 2\epsilon}{1\pm\cos 2\epsilon} \quad (0<\epsilon<\pi/4), \qquad (107)$$

where the upper sign or lower sign holds according as the adjustment is made to brightness or darkness of the field of view.

An identical expression holds for the Chauvin analyzer.[33] If the conditions given by Eq. (102) hold there is, however, a difference—the Chauvin being slightly less sensitive. The influence of multiple reflections on the half-shadow sensitivity may be entirely ignored.

The Sénarmont compensator without a half-shadow device has a sensitivity of $\pm 5\times 10^{-3}\cdot 2\pi$, whereas with such a device the sensitivity is about $\pm 5\times 10^{-5}\cdot 2\pi$. The accuracy, taking reflections into account is, according to Gabler and Sokob, ± 8 percent but may in certain cases be considerably greater.

[33] Since s is dependent on the angle ϵ, which may be easily changed, this gives the Chauvin analyzer the decided advantage of variable sensitivity.

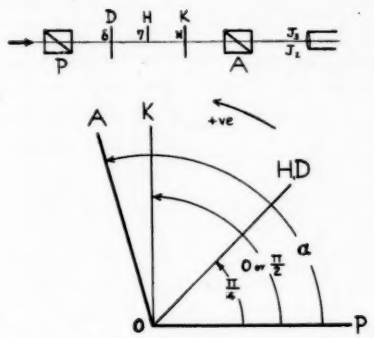


FIG. 16. The optical system and azimuths of the directions of vibration for the Richartz compensator; P, polarizer; A, analyzer; D, plate under test; H, half-shadow plate; K, compensator plate; OP, OA, OD, OH, and OK their respective vibration directions. δ, η, and κ are the phase differences produced by D, H, and K, respectively.

The Quarter-Wave Compensators of Richartz[34]

I. *The Modified Quarter-Wave Compensator*

This is almost identical in form to the arrangement A of the modified Brace compensator but the compensator plate is a $\lambda/4$ plate for the wave-length used. The theory of this instrument is similar to that discussed in the next paragraph.

II. *The New Quarter-Wave Compensator*

In this compensator the idea used in the De Forest Palmer compensator is applied to the modified quarter-wave compensator. The arrangement, shown in Fig. 16, consists of a half-shadow plate H, a compensator plate K, and an analyzer. The plates H and K, are rotatable and are attached to graduated circles which, in conjunction with a vernier, enable the azimuths to be accurately set. The analyzer is also capable of rotation and its azimuth may be read to within 10″. H is a glass slip which may be subjected to tension and has, therefore, a variable phase difference—that of K is constant of value $\pi/2$.

Suppose now that plate D of unknown phase

[34] M. Richartz, Zeits. f. Instrumentenk. **60**, 357 (1940); J. Opt. Soc. Am. **31**, 292 (1941).

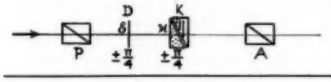
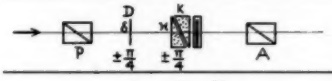
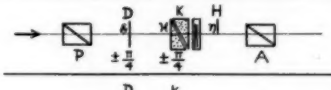
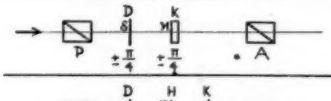
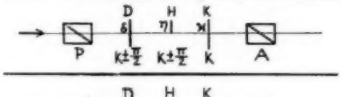
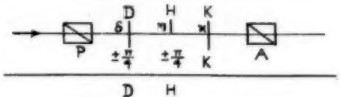
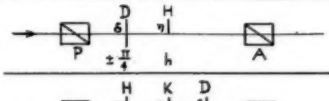
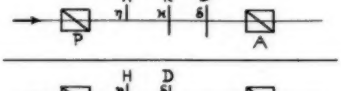
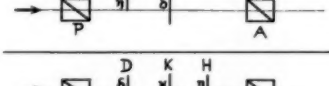
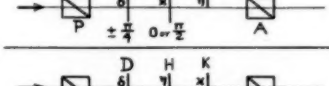
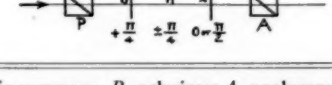
Compensator and type	Arrangement	Position of polarizer and analyzer	Lower limits of sensitiveness	Instrumental constants
Babinet (directly compensating)		Crossed	$7\times10^{-3}\cdot2\pi$ to $1\times10^{-3}\cdot2\pi$	
Soleil (directly compensating)		Crossed	$7\times10^{-3}\cdot2\pi$ to $1\times10^{-3}\cdot2\pi$	
Soleil and half-shadow. (directly compensating)		Crossed	$5\times10^{-4}\cdot2\pi$ to $7\times10^{-5}\cdot2\pi$	
Rayleigh		Crossed	$6\times10^{-5}\cdot2\pi$ with half-shade device $5\times10^{-5}\cdot2\pi$	
De Forest Palmer (directly compensating)		Crossed	$5\times10^{-6}\cdot2\pi$	
Brace (compensator azimuth) for all possible combinations see Fig. 10		—	$5\times10^{-5}\cdot2\pi$ to $3\times10^{-5}\cdot2\pi$	$\kappa\leqq2\pi/60$ η between $2\pi/160$ and $2\pi/360$
Szivessy (compensator azimuth)		Crossed	$5\times10^{-3}\cdot2\pi$ to $3\times10^{-5}\cdot2\pi$ for values of η of $1\times10^{-1}\cdot2\pi$ to $5\times10^{-3}\cdot2\pi$	η always between 0 and $\pi/2$
Modified brace (analyzer azimuth) (can also use sequence *DHK*)		—	$3\times10^{-5}\cdot2\pi$ to $2\times10^{-5}\cdot2\pi$	arrangement *A* η between $3\pi/2$ and 2π $\kappa\leqq1\times10^{-2}\cdot2\pi$ arrangement *B* $\eta\leqq\pi$, $\kappa\leqq1\times10^{-2}\cdot2\pi$
Modified Szivessy (analyzer azimuth)		—	$3\times10^{-5}\cdot2\pi$ to $2\times10^{-5}\cdot2\pi$ depending on η	$\eta\leqq\pi/2$
Sénarmont (analyzer azimuth)		—	without *H* $5\times10^{-3}\cdot2\pi$ with *H* $5\times10^{-5}\cdot2\pi$	$\kappa=\pi/2$ $\eta=\pi$ (Chauvin)
Richartz new quarter-wave (analyzer azimuth)		—	$8\times10^{-6}\cdot2\pi$	$\kappa=\pi/2$ η variable

FIG. 17. Diagrammatic summary. *P*, polarizer; *A*, analyzer; *D*, plate under test; *H*, half-shadow plate; *K*, compensator plate. δ, η, and κ are the phase differences.

difference is placed in position in azimuth $\pi/4$. If H is in azimuth $\pm\pi/4$ and K in azimuth 0 or $\pi/2$, denoting the intensities of the two halves of the field of view by J_2 and J_3, respectively, from Eq. (10) we get with the substitutions $\gamma_1=\gamma_2=\pi/4$, or $\gamma_1=-\gamma_2=\pi/4$, $\gamma_3=0$ or $\pi/2$; $\varphi=\alpha$; $\delta_1=\delta$, $\delta_2=\eta$, $\delta_3=\pi/2$,

$$J_3=\cos^2\left(\alpha\pm\frac{\delta\pm\eta}{2}\right), \tag{108}$$

$$J_2=\cos^2(\alpha\pm\delta/2). \tag{109}$$

For the half-shadow position ($J_2=J_3$), the analyzer azimuth $\bar{\alpha}$ must satisfy the relation

$$2\bar{\alpha}=\pi\mp(\delta\pm\eta/2). \tag{110}$$

In Eqs. (108)–(110) we write $+\eta$ or $-\eta$ according to whether $\gamma_1=\gamma_2=\pi/4$ (fast directions of H and D coincide) or $\gamma_1=-\gamma_2=\pi/4$ (fast directions of H and D perpendicular), respectively, whereas the upper or lower sign holds if $\gamma_3=\pi/2$ (K in azimuth $\pi/2$) or $\gamma_3=0$ (K in azimuth 0), respectively.

Now initially let the azimuths be $\gamma_1=\pi/4$,

$\gamma_2=-\pi/4$, $\gamma_3=\pi/2$, or 0, then if H is strained until $\eta=2\delta$, a half-shadow position will occur for an analyzer azimuth $\bar{\alpha}_0$ given by

$$2\bar{\alpha}_0=\pi. \tag{111}$$

If H is rotated through $\pi/2$, i.e., $\gamma_2=\pi/4$, the half-shadow azimuth $\bar{\alpha}_1$ is now given by

$$2\bar{\alpha}_1=\pi\mp 2\delta, \tag{112}$$

i.e.,

$$\bar{\alpha}_1-\bar{\alpha}_0=\mp\delta. \tag{113}$$

We can now formulate the procedure for measurement of δ. The plates D, H, and K are so arranged between crossed polarizer and analyzer that the azimuth of H is $+\pi/4$ and that of D is $-\pi/4$. Suppose the analyzer drum reading is p_0. If now H or D is rotated by $\pi/2$ and the analyzer adjusted to the half-shadow position reading p_1, then from Eq. (113)

$$p_1-p_0=\delta.$$

A repetition with K in zero azimuth serves to check the results.

The half-shadow sensitivity of the compensator is found from Eqs. (11), (108), (109), and (110) to be $4\cot\delta/2$, from which it is evident that s increases as δ decreases.

The lowest limit to δ which is measurable depends mainly upon the graduated circle for the analyzer. If, as mentioned by Richartz, it is possible to obtain a value of p_1-p_0 of 10 sec. of arc this corresponds to a value of $8\times10^{-6}\cdot2\pi$ for δ and $10^6/4\pi$ for s.

CONCLUSION AND ACKNOWLEDGMENT

The information contained in this article is briefly summarized in Fig. 17. The author wishes to express his thanks to Professor A. M. Taylor for his interest throughout the preparation of this paper, and to Dr. K. Kellner who was always ready to help with translations from the German.

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 1 JANUARY, 1948

The Relation between Efficiency and Exciting Intensity for Zinc-Sulphide Phosphors

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(Received July 29, 1947)

The effect of the intensity of the exciting radiation on the efficiency of zinc-sulphide phosphors activated with silver and containing varying amounts of cobalt below $4 \cdot 10^{-4}$ percent has been studied at temperatures between −180° and 100°C. The results are in agreement with the theory of hole migration and show that the rate of recombination of electrons with ionized killing centers is much faster than that of electrons with ionized silver centers. From the change of intensity dependence with temperature between 0 and 100°C the distance between the activator level and the full band was found to be 0.37 ev. To explain an anomalous result at low temperatures with high Co concentrations, it is suggested that shallow electron traps are present in the zinc-sulphide lattice.

I. INTRODUCTION

IT was shown first by Riehl[1] that the fluorescence intensity of a zinc-sulphide phosphor is not always proportional to the intensity of the exciting radiation and that the efficiency of the phosphor sometimes decreased with decreasing exciting intensity, particularly at temperatures at which temperature quenching begins to set in. His observations were lately confirmed over a wide intensity range by F. Urbach, A. Urbach, and M. Schwartz.[2] An explanation has been suggested by Klasens.[3] To give a short outline of this theory we will make use of the well-known energy diagram given in Fig. 1. Between the uppermost filled band, A, and the next highest empty band, B, there are localized levels, C, caused by the introduction of activators such as silver. Normally these levels are occupied by electrons. On excitation some electrons may be raised into the empty band B with the resultant formation of "holes" at C. Light is emitted when an electron falls back from the conduction band B into this hole. The wave-length of the emitted light is a function of the position of the impurity level in the energy diagram. Klasens assumed, as Schön[4] also did, that there is a second process by which such a hole in an activator level may be filled, namely, by the raising of an electron from the filled band A by temperature agitation. He furthermore assumed that there are usually a small number of impurity centers in the phosphor which introduce energy levels further above the filled band than those of the activator. A hole transferred from level C to the filled band travels through the lattice until it is finally found in such a level D (process b) or another level C (process b'). Recombination of an electron from the conduction band with a hole in level D (process c) can either be radiationless, which means that all energy released by process c is lost as heat, or be accompanied with the emission of a light quantum of a magnitude different from that emitted by process a. The electron transitions may be direct from the conduction band to the levels of C and D, and then one would expect the radiation from D to have the longer wave-length.

Levels of the first kind are caused, for instance, by the introduction of small amounts of copper, while the introduction of cobalt or nickel gives rise to levels of the second kind. It is quite likely that even if the presence of killers such as nickel and cobalt can be completely avoided there are still some killing levels left caused by other irregularities in the zinc-sulphide lattice (such as surface levels, etc.). The probability of a hole leaving level C increases rapidly with temperature, while the probability of a hole leaving level D may still be very small because of its greater height above the filled band. The net result is a transfer of holes from C to D. Thus, with a rise in temperature either the fluorescence is quenched or its color changes, depending on the nature of D. A change of color with change in exciting intensity is also a well-known phenomenon for double activated zinc-

[1] N. Riehl, Zeits. f. tech. Physik **20**, 152 (1939).
[2] F. Urbach, A. Urbach, and M. Schwartz, J. Opt. Soc. Am. **37**, 122 (1947).
[3] H. A. Klasens, Nature **158**, 306 (1946).
[4] H. Schön, Zeits. f. Physik **119**, 463 (1942).

sulphide phosphors. It has been described for instance by Gisolf and Kröger.[5]

Figure 2 demonstrates such a change in a zinc-sulphide phosphor activated with copper and giving the blue and green emissions caused by this activator.

It is seen that an energy transfer has taken place from the blue to the green band with decrease of the excitation energy. The efficiency of the blue band has decreased while that of the green band has increased. This has already been explained qualitatively by Schön,[4] using Fig. 1, in which C and D may represent the levels of the blue and green centers, respectively. The reaction (a) then causes the blue emission. This reaction is of a bimolecular nature, being proportional both to the concentration of blue holes and electrons in the conduction band. Some of the blue holes, however, migrate to green centers through reaction (b), which is of a monomolecular nature, being proportional to the concentration of blue holes only. Thus the speed of (a) diminishes more rapidly than that of (b) with decreasing exciting intensity, since both the number of free electrons and of the blue holes are decreasing. Hence the loss of efficiency of the blue band, which is compensated by an increase in the efficiency of the green emission. Since not all holes travel to green centers but migrate to killing centers also present in the phosphor, this compensation is only partial. If there are no green centers, all energy loss of the blue band will appear as heat produced in radiationless transitions at killing centers.

Klasens has given a simple formula for the quenching of the blue band:

$$\frac{I}{\mu J}=\frac{1}{1+c(\beta_1 J)^{-\frac{1}{2}}},$$

where I = intensity of the blue band $=\beta_1 n n_1$, n_1 = number of holes in "blue centers" per cm³, n = number of free electrons per cm³, J = intensity of exciting radiation, β_1 = recombination coefficient for blue centers, μJ = number of blue centers excited per second and per cm³, c = constant proportional to the number of killing centers and to $e^{-E/kT}$, and E = distance between the level of the blue centers and the full band.

[5] J. H. Gisolf and F. A. Kröger, Physica **6**, 1101 (1939).

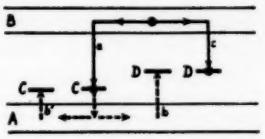

FIG. 1. Energy diagram for luminescence of zinc sulphide phosphors containing two kinds of impurity levels. ● electron, ○ hole, → electron movement, → hole movement.

This equation is the simplest possible for explaining the change of I with temperature and exciting intensity. It is, however, only valid under certain conditions—namely, that the holes move instantaneously through the full band and that the reaction coefficients, β_1 and β_2, for the recombinations of electrons with blue and killing centers, respectively, are the same. Accurate measurements have now been made of the intensity of blue fluorescence of zinc-sulphide phosphors containing silver luminescence centers and nickel and cobalt killing centers to see whether these conditions hold and whether the theory of hole migration can explain the results. The measurements will be described in detail below. In a subsequent paper[6] a more general theory of hole migration will be presented.

II. APPARATUS AND METHOD

a. Exciting Radiation

A 125 w Philips MB/W lamp, consisting of a high pressure mercury arc in quartz in an outer nickel oxide glass envelope, was used as source of the exciting ultraviolet radiation. This source is stable and gives approximately mono-

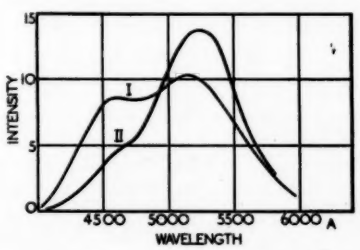

FIG. 2. Curve I: spectral distribution of a ZnS-Cu phosphor at "high" exciting intensity. Curve II: spectral distribution of the blue phosphor under emitting intensity 10 times lower. The fluorescence intensity has been plotted on a 10 times larger scale.

[6] M. E. Wise and H. A. Klasens, to be pudlisheb.

chromatic light with 99 percent of the emitted energy in the wave-length range 3650–3663A, 0.9 percent at 4047A, less than 10^{-4} percent in the range 4200–6900A, and in the range 6900–7900A less than 0.05 percent consisting of mercury lines and radiation from the red-hot quartz and electrodes. A slight amount of energy is also emitted in the near infra-red below 2μ. The red and infra-red radiation was reduced by interposing a 3-mm Chance filter ON 19. This was found more satisfactory than a dilute solution of cupric chloride because of a greater stability and higher ultraviolet transmission.

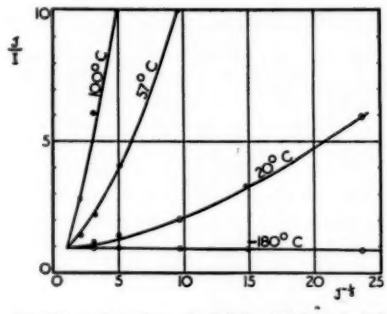

FIG. 3. J/I as function of $J^{-\frac{1}{2}}$ for ZnS containing 10^{-2} percent Ag and 10^{-4} percent Co at different temperatures.

The ultraviolet output of the lamp was found to become stable after running for about one hour, variations of more than 0.5 percent being rare, provided the current of the lamp was kept constant.

The intensity of the exciting light was changed by filters with varying transmission for 3650A. At first photographic plates developed after varying exposures were used, combinations of which give filters of transmissions, varying from 0.3 to 10^{-4} at 3650A. These filters were found, however, to have several disadvantages:

(a) It was difficult to obtain uniformity to within 5 percent.
(b) The filters are diffusing, which makes the measurement of transmission difficult because of scattered light.
(c) The filters luminesced slightly under ultraviolet excitation.
(d) There was a long period change in transmission with time under ultraviolet irradiation.

More satisfactory results were obtained by using selected mica sheets of a very high purity. The sheets had a transmission of about 60 percent for 3650A, were uniform in transmission over a large area, and were not luminescent. Combinations of several sheets were pressed between glass plates and the edges cemented together. The resultant filters were uniform in transmission to within 1 percent.

b. Apparatus for Mounting Phosphors

The phosphor under investigation was dispersed in a thin layer on the closed end of a thin cylindrical metal tube which was surrounded along most of its length by a metal jacket. A detachable glass window opposite the end of the inner tube allowed access to the phosphor and irradiation and observation of the luminescence. The space between the metal tubes could be evacuated, thereby preventing water vapor from condensing on the phosphor and on the glass window at low temperature, and keeping convection losses between inner and outer tube as low as possible. The temperature of the phosphor was measured with a thermocouple attached to the inner tube at a point near the edge of the phosphor layer. The temperature could be kept constant to within 1° at temperatures between room temperature and 200°C by filling the inner tube with butyl phthalate and adjusting the current through a heater element immersed in the liquid. For measurements at low temperature the inner tube was filled with ice or liquid air.

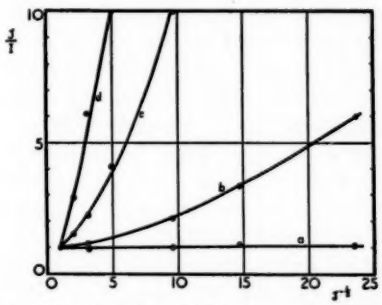

FIG. 4. J/I as function of $J^{-\frac{1}{2}}$ at room temperature for ZnS phosphors activated with 10^{-2} percent Ag and containing: (a) 0 percent Co; (b) 10^{-4} percent Co; (c) $3\cdot10^{-4}$ percent Co; (d) $4\cdot10^{-4}$ percent Co.

c. Measurement of Luminescent Light Intensity

An R.C.A. 931A photoelectron multiplier was used for light intensity measurements. Under

high intensities of radiation the multiplier output showed rapid fatigue, with an extremely slow recovery of about 2 percent per hour. In the fatigued state the multiplier showed linearity of output current with light intensity over a range of illumination of 10^5. The multiplier was therefore first exposed to a high light intensity until a steady state was reached, so that exposure to the highest luminescent intensity caused no further fatigue.

The output of the multiplier was passed through a sensitive galvanometer equipped with a suitable series of shunts. The dark current of the multiplier was balanced out by a tapping from the main multiplier supply system.

The blue band caused by the silver activator in these phosphors must be isolated from unwanted radiations which include:

(a) A faint green emission from the phosphor probably caused by traces of copper noticeable at high temperatures and low exciting intensities.

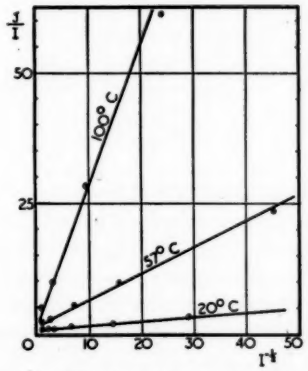

FIG. 5. J/I of Fig. 3 replotted as function of $I^{-\frac{1}{2}}$.

(b) 4047A and 3650A radiation reflected from the phosphor surface and parts of the apparatus.

(c) Red light from the lamp getting through the Chance ON 19 filter.

(d) 5780, 5461, and 4358A radiation getting through the nickel oxide glass of the lamp envelope and being reflected from the phosphor surface.

Two methods were used for eliminating these radiations. One method was to interpose a suitable series of filters between phosphor and photocell. The 3650A radiation was removed by two Chromex 2324 filters; 4047A radiation was removed by two Ilford 809 filters, and Wratten 4 was used to remove 4358A radiation.

Radiation above 6000A was removed by a Chance filter OB 2, and radiation between 6000 and 5600A by a Wratten 39 filter. The resultant radiation which was transmitted by this filter combination was a narrow band of wave-lengths with half-values at 4620A and 4860A.

Precautions were found necessary to remove all traces of grease from the glass window of the apparatus holding the phosphor, to prevent additional unwanted luminescence.

This filter combination still transmits some of the green copper emission, particularly at high temperatures at which the bands are broader, and for accurate measurements it was found necessary to use the monochromator. A wave band of 150A at 4550A was then taken at the exit slit, and the output was measured with the multiplier photo-cell. The range over which the exciting intensities could be varied was, however, smaller, since only a small amount of light could be collected from the phosphor by the aperture of the monochromator.

The double monochromator and electron-multiplier combination was also used in the measurement of the spectral energy distribution.

III. EXPERIMENTAL RESULTS

The intensity of the blue emission of zinc sulphide containing 0.01 percent Ag and varying Co concentrations was measured over a range of temperatures.* According to Eq. (1), straight lines must be expected if J/I is plotted against $J^{-\frac{1}{2}}$. Their slopes give the value of $c/(\mu\beta_1^{\frac{1}{2}})$.

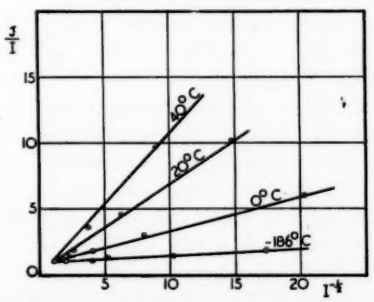

FIG. 6. Intensity dependence of a ZnS phosphor activated with 10^{-2} percent Ag and containing $4 \cdot 10^{-4}$ percent Co.

Figures 3 and 4 give some of the results. In Fig. 3 the intensity dependence is shown for a

* All phosphors had the sphalerite structure.

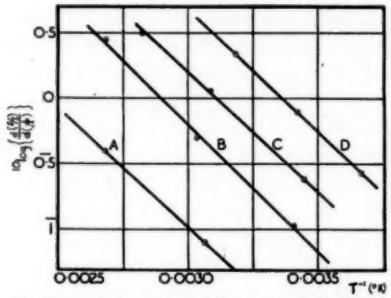

FIG. 7. Temperature dependence of the slopes of the intensity dependence curves for zinc sulphide phosphors activated with 10^{-2} percent Ag and containing: (A) 0 percent Co; (B) 10^{-4} percent Co; (C) $2\cdot10^{-4}$ percent Co; (D) $4\cdot10^{-4}$ percent Co.

ZnS phosphor containing 10^{-2} percent Ag and 10^{-4} percent Co at different temperatures, while Fig. 4 shows the intensity dependence at room temperature for ZnS phosphors containing 10^{-2} percent Ag and different amounts of cobalt. Although the slopes of the lines behave as expected, i.e., increasing with temperature and with Co concentration, the lines are far from straight.

The slope increases with decreasing exciting intensity, showing that the efficiency decreases more rapidly than expected from Eq. (1). It has already been pointed out that the equation only holds if $\beta_1=\beta_2$. In that case the number of free electrons is independent of the distribution of the holes among the centers (provided the number of holes in the filled band is very small). If, however, β_2 is larger than β_1, the migration of holes from silver centers to cobalt centers will be accompanied by a decrease of the number of free electrons, since in a phosphor with only one kind of center the number of free electrons n is proportional to $(J/\beta)^{\frac{1}{2}}$. This decrease of n causes an extra decrease of the intensity of the blue band in accordance with the observations.

From an analysis of many curves like those of Figs. 4 and 5 it was deduced[6] that $\beta_2\gg\beta_1$, and that a linear relationship can then be expected over a wide intensity range not between J/I and $J^{-\frac{1}{2}}$ but between J/I and $I^{-\frac{1}{2}}$. Replotting the values of J/I of Fig. 3 against $I^{-\frac{1}{2}}$ does indeed give straight lines. The temperature dependence of the phosphor was measured at the same time for the highest exciting intensity and was used to give the relation of the absolute efficiencies at the different temperatures. These measurements were carried out with the filter combination which transmits a small part of the green band. The fluorescence intensity therefore appears too high at low exciting intensities and high temperatures. This was found disturbing, especially in the phosphors containing higher amounts of cobalt. Further measurements were therefore carried out with the monochromator as described above, thereby limiting somewhat the range of intensities.

Figure 6 gives the result for a phosphor activated with 10^{-2} percent Ag and containing $4\cdot10^{-4}$ percent cobalt. The measured points lie on straight lines over the measured intensity range.

One may expect the slope of the lines to be proportional to $e^{-E/kT}$.[6] It is therefore possible to find the value of E by plotting the log of the slopes against $1/T$. This is done in Fig. 7 for four phosphors with different amounts of Co.

The resulting E values are:

	% Ag	% Co	E
A	10^{-2}	0	0.368 ev
B	10^{-2}	10^{-4}	0.388 ev
C	10^{-2}	$2\cdot10^{-4}$	0.365 ev
D	10^{-2}	$4\cdot10^{-4}$	0.372 ev

The values of E are thus found to be fairly close with an average of about 0.37 ev.

Anomalous results are obtained with phosphors containing a high percentage of cobalt, particularly at low temperatures. This can be seen from the intensity dependence of the phosphor containing $4\cdot10^{-4}$ percent Co at liquid air temperature, as given in Fig. 6. The slope of this line is greater than that predicted by extrapolating curve *D* of Fig. 7. The deviations with phosphors containing still greater amounts of cobalt are more pronounced. Sometimes anomalous results were found with lower cobalt concentrations when the phosphors were prepared differently. In all cases an apparently lower E value is found. It seems improbable that the E value for these phosphors is really lower, for the spectral distribution of the blue band is the same for all our ZnS-Ag phosphors irrespective of the cobalt concentrations, whilst it is likely that a change in E would be accompanied by a shift of the blue band.

The results can be explained on the assumption that by introducing cobalt the lattice is so much disturbed that a large number of shallow electron traps are formed, especially if the temperature of firing is not kept high enough.

Such traps would not influence the movement of electrons above a critical temperature.[7] Below this temperature, however, the electrons may spend a considerable time in traps, thereby lowering their effective speed of movement through the conduction band, and thus the value of β_1. The probability for a hole to escape from a silver level is thereby enhanced, resulting in a greater loss of efficiency for the blue band. Further evidence for the presence of such traps can be derived from the shapes of the temperature dependence curves, which change in character below a critical temperature range, and from the buildup of fluorescence, which is very slow at high cobalt concentrations. More details about these effects will be published later.

We are indebted to Dr. Rothschild who prepared the phosphor samples used in this study. We also wish to thank Mr. J. A. M. van Moll and the Directors of Philips Lamps, Ltd. for permission to publish this work.

[7] H. A. Klasens and M. E. Wise, Nature **158**, 483 (1946).

Symposium on Modern Instrumental Methods of Analysis

THE Minnesota Section of the American Chemical Society and the Institute of Technology of the University of Minnesota are presenting a symposium on Modern Instrumental Methods of Analysis to be held in Minneapolis on March 22, 23, and 24, 1948. Persons interested in attending the symposium or in obtaining a copy of the complete program should communicate with Professor William N. Lipscomb, Chairman of the Symposium Committee, Division of Physical Chemistry, University of Minnesota, Minneapolis 14, Minnesota.

Symposium on Molecular Structure and Spectroscopy

A SYMPOSIUM on Molecular Structure and Spectroscopy will be held at the Mendenhall Laboratory of Physics at The Ohio State University from June 14 through June 19, 1948. The program will include discussions of the interpretation of molecular spectroscopic data as well as methods for obtaining such data. There will also be sessions devoted to other phases of spectroscopy of current interest. Further information and a copy of the program when it becomes available can be obtained by writing to Professor Harald H. Nielsen, Mendenhall Laboratory of Physics, The Ohio State University, Columbus, Ohio.

Letters to the Editor

A New Principle in Interferometer Design

EDSON R. PECK
Northwestern University, Evanston, Illinois
August 8, 1947

AN interferometer with new properties has been constructed by replacing each one of the two mirrors of a conventional Michelson interferometer by a pair of plane, front-surface mirrors mounted to form a right angle. Optical path difference in such an instrument is independent of rotation of either mirror pair about the intersection line of its two surfaces.

Figure 1 is a diagram of the instrument, and Fig. 2 is a photograph of sodium light fringes obtained with it.

Preliminary adjustment of the right angle of each mirror pair may be made separately by use of a telescope, the criterion being coincidence of the two images of an object seen by reflection. It is then sufficient for the final critical adjustment upon the fringes to adjust the angle of only one of the pairs. Compensation for slight deviation from 90° in one pair is made with the other.

Two angular adjustments of one pair relative to the other are required. The lateral angle of the intersection line of a pair about the line of sight to the pair is not critical. The angle between the intersection line and the line of sight is as critical as an angular adjustment of the conventional interferometer, and is made in the usual way.

One other degree of freedom is the distance between the intersection line of one pair and the image of the intersection line of the other pair as zero order is passed. If this distance is not zero, fringes near zero order have the appearance of parallel, straight lines at infinity. Constancy of the spacing of these fringes, as the eye is moved parallel to them, is a test for correct lateral angular adjustment mentioned above. The distance between intersection lines at zero order is not important so far as formation of good circular fringes far from zero order is concerned; it simply affects the direction of the center of the pattern.

An important feature of the instrument is that one of the mirror pairs may be carried by a rotating arm, and thus an angular motion may be controlled by interferometric measurement of chord length. Also, in spite of the seeming increased complexity of the new interferometer, it seems to retain its adjustment better than the conventional type. This is because there is only one critical adjustment concerned with the relative orientation of the two pairs, as against two such adjustments in the usual instrument. The second critical adjustment here is concerned with the two mirrors within a pair, and hence is easy to maintain.

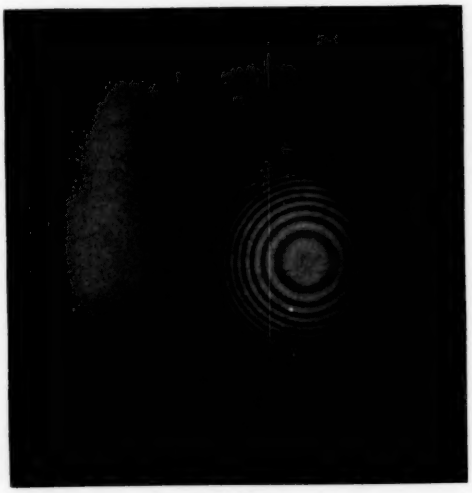

FIG. 2.

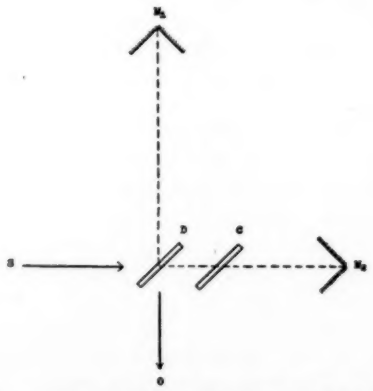

FIG. 1. S = source, O = observer, D = dividing plate, half = silvered, C = compensating plate, and M_1, M_2 = mirror pairs.

An interferometer is also possible in which each mirror is a triple set forming corner right angles. In such an instrument no angular adjustment whatever is needed for relative orientation of the two mirror sets.

As an approximation to this ideal, an interferometer has been constructed using glass corner-cube prisms instead of front-surface reflectors. Here the situation is complicated by refraction; yet both analysis and experiment show that the fringes are still in focus at infinity regardless of orientation of the prisms. Good circular fringes are obtained without fine angular adjustment, provided the prisms are roughly mounted so that the light enters nearly normally to the glass surface. If the angle of incidence on one prism is made fairly large (~20°) the fringes are approximately elliptical or hyperbolic.

This interferometer was developed for use with a recording spectrometer in connection with a project sponsored by the Bureau of Ships of the U.S. Navy.

Questionnaire on Illumination

KASSON S. GIBSON
National Bureau of Standards, Washington, D. C.
October 18, 1947

THE following questionnaire has been sent by the United States Technical Committee 7 of the International Committee on Illumination to the various national committees. A meeting of the I.C.I. has been scheduled for July 1 to 7, 1948, in Paris. Secretariat committees have the responsibility for making recommendations on the subjects assigned to them. We have asked the various national committees (or their respective technical committees on colorimetry and artificial daylight) to submit replies to the questionnaire by January 1, 1948.*

1. Proposed Standard Illuminant E

At the tenth session of the International Committee on Illumination at Scheveningen in 1939 it was recommended that the national committees study the advantages which the use of standard illuminant E would present as a substitute for standard illuminants B and C, to represent a generally satisfactory artificial daylight, and to serve as a common basis whenever it is necessary to characterize the color of an object for the purpose of international comparisons.

A. The proposed new illuminant E ($x=y=z=0.3333$) is realized by combining I.C.I. illuminant A (2848°K) with a specified Davis-Gibson filter, in a manner similar to the realization of illuminants B and C. Many in the United States are opposed to the substitution of the proposed illuminant E for standard illuminant C in the colorimetry of non-self-luminous objects.

Do you favor or disfavor the adoption of a new standard illuminant E for the colorimetry of non-self-luminous objects?

B. In the colorimetry of light sources there appears to be some advantage in the use of the point ($x_w=y_w=z_w=0.3333$) representing the equi-energy source as the achromatic point for the determination of dominant wavelength and purity.

Do you favor the adoption of illuminant E for the achromatic point in the colorimetry of light sources, or would you prefer that the hypothetical equi-energy source be used for this purpose?

2. Colorimetric Purity

A second recommendation of the 1939 session of the I.C.I. was that the factor of colorimetric purity be represented by the symbol, p, and be calculated by the formula:

$$p=(y_d/y)(y-0.3333)/(y_d-0.3333)$$

in which y is the second trichromatic coordinate of the standard 1931 I.C.I. colorimetric coordinate system for the color stimulus to be specified and y_d is the second trichromatic coordinate for that part of the spectrum required to be mixed with the so-called equal-energy source to match the color stimulus to be specified—or for the mixture of the long wave and short wave extremes of the spectrum required to be mixed with the equal-energy source to match the color stimulus to be specified.

In considering the recommendations adopted at Scheveningen the United States National Committee, at its meeting, November 10, 1939, recorded a negative vote with respect to this recommendation for two reasons: First, the correlation between colorimetric purity and the saturation of the object-color perception is lost if the basic stimulus is different in chromaticity from the illuminant; second, the proposed formula becomes indeterminate for $y_d=0.3333$. The United States National Committee proposed the following revised recommendation:

"It is recommended that colorimetric purity be represented by the symbol, p, and be calculated by the formula: $p=(y_d/y)F$, where

$$F=(y-y_w)/(y_d-y_w) \quad \text{or} \quad (x-x_w)/(x_d-x_w),$$

depending upon which numerator has the greater absolute value. (x, y, z) are the trichromatic coordinates in the standard 1931 I.C.I. colorimetric coordinate system for the light to be specified. (x_w, y_w, z_w) are to be taken as the trichromatic coordinates of standard illuminant E (0.3333, 0.3333, 0.3333) for light arising from self-luminous bodies, and for light reflected from objects, shall be the trichromatic coordinates of the illuminant. (x_d, y_d, z_d) are the trichromatic coordinates of the point on the spectrum locus, or on the straight line joining its extremes, representing the light required to be mixed with light of trichromatic coordinates (x_w, y_w, z_w) to match the light to be specified."

Do you agree with either of these recommendations or do you have another wording to suggest?

3. Standard Observer

Do you have any scientific evidence or practical experiences that indicate that the standard observer fails to represent normal observers satisfactorily?

4. Standard Illuminants

A. In view of the possible influence of ultraviolet irradiation on the colors of fluorescent samples, do you believe that the definition of standard illuminants A, B, and C should be made more precise in regard to the ultraviolet?

B. In view of the growing use of fluorescent materials and of light sources that are rich in ultraviolet energy, such as MCF/U lamps, do you believe that an additional standard illuminant differing from illuminants A, B, and C, by having relatively more ultraviolet energy, should be established?

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* Secretariat: United States Technical Committee No. 7. Replies to the questionnaire should be sent to the Secretariat Committee, Dr. K. S. Gibson, Chairman, National Bureau of Standards, Washington 25, D. C.

5. Illuminant for Color Matching

For commercial color matching, is it your practice to use chiefly (a) one or the other of the standard illuminants A, B, or C, (b) some other combination of filter with an incandescent lamp, (c) some fluorescent lamp, (d) some phase of natural daylight, or (e) some other light source?

6. Specification of Color-Rendering Properties

Has any recognized method been developed to indicate the degree to which artificial daylight produces a rendering of object colors in conformity to that produced by one of the standard illuminants?

7. Color Discrimination

The various national committees are requested to supply such data on discriminability of various colors and on ways of distorting the XYZ lattice to yield approximately uniform color scales as have been obtained since 1939. These data will be summarized by the United States Committee for consideration at the 1948 meeting.

8. Color Terminology

It is recognized by the United States Committee that discussion of color terms at the 1948 meetings of the I.C.I. might have the very desirable result that divergent usage in the various nations would be reduced, or even for some color concepts eliminated. To keep the discussion within reasonable bounds, however, it is proposed to limit discussion to the nine psycho-physical and five psychological concepts defined below:

PSYCHO-PHYSICAL

A. (Color, colour, couleur)—the characteristics of light other than spatial and temporal inhomogeneities (light being that aspect of radiant energy of which a human observer is aware through the visual sensations that arise from the stimulation of the retina of the eye).

B. (Luminance, photometric brightness, brilliance)—luminous flux emitted per unit solid angle and unit projected area of the source.

C. (Directional luminous reflectance, luminance factor, albedo)—the luminous reflectance that an ideal perfectly diffusing surface would need to possess in order to yield the same luminance as the test specimen under the same illuminating and viewing condiitons.

D. (Dominant wave-length, lambda-dominante)—the wave-length of the portion of the spectrum that, when combined with achromatic light in suitable proportions, matches the color.

E. (Complementary wave-length)—the wave-length of the portion of the spectrum that, when combined with a sample color in suitable proportions, matches the adopted achromatic light.

F. (Purity, pureté)—the relative luminances of the spectrum and neutral components in the mixtures mentioned in the definitions of dominant wave-length and complementary wave-length. (Note: Various scales of purity are used, all of which can be expressed as some mathematical function of the ratio of the components; for example, excitation purity, often called simply purity, is the ratio of the distance on the I.C.I. standard chromaticity diagram between the neutral point and the sample point to the distance in the same direction between the neutral point and the spectrum locus or the purple boundary.)

G. (Chromaticity, chromaticité)—the quality of color specified by dominant wave-length and purity (alternatively complementary wave-length and purity) taken together.

H. (Tristimulus values, tristimulus coefficients, valeurs tristimulus)—the amounts of the primaries required to establish a match with the sample, either by addition of all three, or addition of one primary to the sample to match any pair of primaries, or the addition of any pair to the sample to match the remaining primary. (Note: By American practice the tristimulus values of a color are designated X, Y, Z. By British practice, the match for a color, C, is given in the form: $C=uX+vY+wZ$, where u, v, w, are the tristimulus coefficients.)

I. (Chromaticity coordinates, trichromatic coefficients, trichromatic coordinates, trilinear coordinates, x, y, z)—the ratio of any one of the tristimulus values for a sample to the sum of the tristimulus values.

PSYCHOLOGICAL

J. (Brightness, luminosity, brilliance, phanie)—the attribute of the color perception of a self-luminous area that permits it to be classified as equivalent to some member of achromatic color perceptions ranging from very dim to very bright. (Note: This is the psychological correlate of the psycho-physical term *luminance*.)

K. (Lightness, leucie, luminesse)—the attribute of an object-color perception that permits it to be classified as equivalent to some member of the series of grays ranging between black and white. (Note: This is the psychological correlate of the psycho-physical term *directional luminous reflectance*.)

L. (Hue, tonalité chromatique)—the attribute of a color perception that determines whether it is red, yellow, green, blue, purple, or the like. (Note: The psycho-physical term *dominant wave-length* correlates fairly well with this psychological concept.)

M. (Saturation)—the attribute of any color perception possessing a hue that determines the degree of its difference from the achromatic color perception most resembling it. (Note: If the remaining attributes of the color perception such as hue and lightness are kept constant, saturation correlates well with the psycho-physical term *purity*.)

N. (Chromaticness, chromie, chromatesse)—the quality of a color perception specified by hue and saturation taken together. (Note: This is the psychological correlate of the psycho-physical term *chromaticity*.)

In the above list the terms in parentheses are those either used or proposed for the corresponding definition. The various national committees are requested to indicate what term, if any, they would recommend for these definitions. Comments on the definitions themselves are also solicited.

A Transmitting Polarizer for Infra-Red Radiation

N. WRIGHT
The Dow Chemical Company, Midland, Michigan
October 16, 1947

A RECENT publication of Elliott and Ambrose[1] describes a polarizer for infra-red consisting of three transmitting films of selenium inclined at the proper angle.

A similar polarizer, perhaps more easily assembled, consists of a transmitting pile of three crystalline AgCl plates inclined at an angle of 26.5° to the beam direction. For this purpose sheets of crystalline AgCl 1 mm (or less) in thickness and of any area desired can be obtained commercially.[2] This pile produces a high degree of polarization throughout the rocksalt range (visible to 15μ) and suffers little loss because of absorption. Tests at greater wave-lengths have not been made.

Researches of the sort described by the above authors[1] on oriented plastics and on single crystals are being carried out in this laboratory using the AgCl polarizer, and these are to be described later. The method yields information on the positions of hydrogen atoms, and in this way it complements the method of x-ray diffraction, which falls short in this respect because of the low scattering power of hydrogen atoms.

[1] A. Elliot and E. J. Ambrose, Nature **159**, 641 (1947).
[2] Harshaw Chemical Company, Cleveland, Ohio.

Comments Regarding "A New One-Step Photographic Process" by Edwin H. Land

LLOYD E. VARDEN
Pavelle Color, Inc., New York, New York
June 20, 1947

A NORWEGIAN patent[1] of the German firm, I. G. Farbenindustrie A.G., published October 25, 1943, claims priority from the early part of 1941 on the principles utilized by Land[2] in his one-step photographic process. I shall not discuss this patent (or others which are referred to later) in detail, since I have a complete article in preparation for subsequent publication in the Journal of the Photographic Society of America. However, a few quotations from the patent seem in order.

In the disclosures of the patent the following statements are made:

> If a hardened silver halide layer is applied over a hard gelatin layer that contains small quantities of colloidal silver, then after treatment with a developer containing sodium thiosulphate (hypo) and washing off of the hardened emulsion layer with warm water, the negative of the picture copied on the top layer can be observed on the bottom layer in a yellow to brown color. It is also possible, for example, to prepare the two layers separately and, after soaking with a developer containing sodium thiosulphate, bring them into intimate contact with each other by pressing them together, and then separate them again after a short interval of time. Upon the further addition to one or both layers substances, such as sodium sulphide, mercaptobenzthiazole or the like, that produce a silver salt difficultly [*sic.*] soluble in the fixing thiosulphate, it is possible to effect the precipitation of the silver in the bottom gelatin layer in a strongly covering black form instead of in yellow.
>
> This process is specially suitable for making a positive at one and the same time when making (developing) a negative.
>
> The developer must contain substances that dissolve the silver halide, e.g., sodium thiosulphate, and in certain circumstances even a concentrated alkaline sulphite solution is sufficient. It is advisable to employ a very rapidly acting developer in order that the developer's first attack, and the development of the first picture trace, may take place more quickly than the simultaneously occurring solution of the silver halide.
>
> Since the process only calls for one treatment bath, the making of positives takes place very simply and very rapidly and it is therefore also particularly suited for operation by machine.

Three examples are given, with developer formulas, plus a description of how the process can be adapted for highly sensitive layers.

There are four claims in the patent, the first of which reads as follows:

> (1.) Processes for making photographic positive pictures, characterized in that the unexposed silver halide in a negative layer, accordingly not reducible by the developer, is brought into solution with additions such as fixing thiosulphate (hypo) during the developing process, and in that the dissolved silver salts are made to precipitate in another layer that is free from silver halide and that is in intimate contact with the negative layer, either by means of substances such as sodium sulphide which with silver salts provide difficultly [*sic.*] soluble compounds, particularly colored compounds difficultly [*sic.*] soluble in the fixing bath, or by means of additions such as colloidal silver which as 'rings' effect a reduction, or else by means of both methods.

Another Norwegian Patent[3] assigned to the I. G. Farbenindustrie, which was an addition to the main patent, was published August 6, 1945, and claimed priority from January 21, 1943.

A patent[4] issued in this country to A. Rott, Berchem-Antwerp, Belgium, is so closely allied to the main Norwegian Patent granted to I. G. that it should be mentioned here also. The application of Rott's patent was somewhat later than that of I. G.'s (July 21, 1941 against January 24, 1941).

Rott employed a developing solution containing sodium thiosulfate as a silver halide solvent for the transfer of the undeveloped halides to a light-insensitive reception surface containing a fogging agent. As fogging agents for the positive forming material he mentions colloidal silver, colloidal forms of sulfur, silver sulfites, hypophosphite, stannous chloride, and organic sulfur compounds, such as thiosinamine, capable of splitting off sulfur as a bivalent

ion. Ordinary coated paper is stated to be satisfactory for the positive reception surface if the developer contains the fogging agent, e.g., 0.005 percent sodium sulfide, in addition to the silver halide solvent.

However, the Rott patent covers a two-step process since his main process claim reads "the process of photographic image transfer which comprises contacting a photographic silver halide layer containing a developing solution and a developed photographic image in the presence of a silver halide solvent and a fogging agent with a reception material which is insensitive to light. Nevertheless, the principle employed is not so far removed from that utilized by Land that it should have been completely ignored by him in his literature citations.

[1] Norwegian Patent No. 66994, "Process and device for making photographic positive pictures," I. G. Farbenindustrie, published October, 1943. Patented in Norway from February 4, 1942. Annual fees and life of patent figured from January 24, 1942. Priority claimed from January 24, February 6, and March 6, 1941 (Germany) under International Convention Law of March 15, 1940 and decree of December 16, 1941.
[2] Edwin H. Land, "A new one-step photographic process," J. Opt. Soc. Am. 37, 61 (1947).
[3] Norwegian Patent No. 69510, "Process for making photographic positive pictures by reflex copying methods," I. G. Farbenindustrie, published August 6, 1945. Patented in Norway from January 20, 1944. Priority claimed under International Convention from January 21, 1943 (Germany).
[4] U. S. Patent No. 2,352,014.

Reply to Lloyd E. Varden's "Comments Regarding 'A New One-Step Photographic Process'"

EDWIN H. LAND

Research Laboratories, Polaroid Corporation, Cambridge, Massachusetts

October 3, 1947

THE Editor of the Journal has been kind enough to give me an opportunity to reply to Dr. Lloyd E. Varden's "Comments regarding 'a new one-step photographic process.'" I welcome the chance of clarifying a point which my paper apparently failed to make clear.

In my paper I undertook to describe a "system of photography" which I characterized as ". . . a camera and a photographic process that would produce a finished positive print, directly from the camera, immediately after exposure. From the point of view of the user, the camera was to look essentially like an ordinary camera, the process was to be dry, the film was to be loaded in one of the usual ways, the positive print was to look essentially like a conventional paper print, and this print was to be completed within a minute or two after the picture was taken." I went on to say that "In photographic literature there appear to be no references to such a system of photography, even as an ideal."

I believe this statement to be quite accurate as it stands. In making it, however, I certainly did not mean to imply that the system I was describing was unrelated to principles already known in photography. On the contrary, one of the ground rules which I set for myself at the beginning of my work on the processes was to use, as far as possible, established and proved principles and materials; the principle, for example, of the catalytic action of the latent image, with its enormous photo-chemical efficiency, embodied in the familiar silver halide emulsions.

Dr. Varden's suggestion that I should not have omitted Rott's work from my list of literature citations raises the question of how far one should go in pointing out those who have previously contributed to an art in which one is engaged.

After a careful examination of the Rott patent and the I. G. Farbenindustrie patents which Dr. Varden quotes, I feel that they are related no more closely to my own procedures than the work of many other previous investigators, certainly fifty and possibly as many as one hundred, a list far too long to be made a part of my article in the Journal.

None of the patents which Dr. Varden cites, and indeed no other publications of which I am aware, describe a one-step process in the sense in which I have used the term, or the methods I proposed for making the process effective: the spreading of a viscous reagent, for example, between positive and negative layers; the use of a rupturable "pod" containing reagent ready for use in the simultaneous development of negative and positive images; ways of protecting the reagent from oxidation over long periods; general methods of stabilizing the pictures without washing them; methods of getting the system to work over a wide temperature range. None of these patents describes how to "produce a finished print directly from the camera immediately after exposure" that would "look essentially like a conventional paper print," how to devise "a process that was to be dry" for use in a camera that was "to look essentially like an ordinary camera . . . to be loaded in the usual way," or how to produce a "finished" positive print (i.e., one requiring no washing or other after-treatment) and complete the print "within a minute or two after the picture was taken."

Stray Radiation in Littrow-Type Spectrometers Which Employ Collimating Mirrors

A. E. MARTIN

Sir Howard Grubb, Parsons and Company, Optical Works, Newcastle-on-Tyne, England

August 28, 1947

A LETTER by H. W. Straat with the above title, published in the June number of the Journal, draws attention to the troublesome effects of stray radiation in these instruments and suggests means of overcoming the difficulty to a very large extent.

We ourselves have for some time been engaged in developing infra-red spectrometers of this type and at an early stage had trouble with stray light. Some of the con-

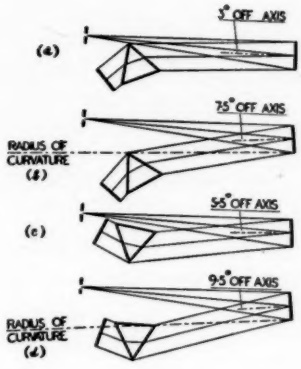

FIG. 1.

siderations which influenced our ultimate design may be of interest in this connection. To fix our ideas we will consider a spectrometer which employs a rock-salt prism of 10-cm face and a collimating mirror of 50-cm focal length, the distance from this mirror to the center of the prism face being 36 cm. The following possibilities are of interest: (1) With the arrangement shown in Fig. 1(a) a very compact instrument is possible, the mirror being used at only 3° off-axis. Quite fair definition is in fact obtained with a spherical mirror instead of the usual off-axis paraboloid. The paraboloid is, of course, very much more difficult to produce and is consequently expensive. Stray light, however, is troublesome in this case, as can be seen from the diagrams in Mr. Straat's letter.

(2) The geometrical arrangement of Fig. 1(b), suggested by Mr. Straat to avoid the stray light encountered in our Fig. 1(a), has one immediate disadvantage—the collimating mirror is now used at 7½° off-axis instead of 3°. An off-axis paraboloid is now essential.

(3) An alternative arrangement, not mentioned by Mr. Straat, but which is favored by some American manufacturers, is to reverse the prism as shown in Fig. 1(c). This layout requires a rather greater off-axis angle (5½°) than in Fig. 1(a), owing to the space taken up by the prism and associated Littrow mirror, but an important advantage is gained, for since the spectrum is reversed, as compared with Fig. 1 of Mr. Straat's letter, any stray light will be of wave-length longer than the wave-length setting of the spectrometer. Under normal conditions of use no harmful result will occur, since the energy falls very rapidly with increasing wave-length from 2μ onwards.

(4) Complete avoidance of re-entrant radiation, with the prism reversed, can be obtained by moving the prism still further away from the slit, but the off-axis angle is now increased to 9½° (Fig. 1(d)).

From our own observations, it would appear that the best over-all compromise is to adopt the arrangement of Fig. 1(c) with an off-axis angle of about 5½°. To obtain the best definition under these conditions a carefully figured off-axis parabolic collimating mirror is employed.

Errata: On Two Accessories of Three-Dimensional Colorimetry

I. The Probable Error of Colorimetric Tensor Components as Derived from a Number of Color Matchings

II. The Determination of the Principle Colorimetric Axis at Any Point of the Color Threefold

[J. Opt. Soc. Am. 36, 464 (1946)]

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I

THROUGH inadvertency, an erroneous formula, Eq. (4), p. 466, has been given for the probable error of $1/g_{11}=2a$. The correct formula is

$$\text{P.E.}(1/g_{11})=2a(2/n)^{\frac{1}{2}}=1/g_{11}(2/n)^{\frac{1}{2}},$$

and its derivation is as follows:

With the principal axes as coordinate axes, the probability function is

$$f=(g_{11}g_{22}g_{33}\pi^{-3})^{\frac{1}{2}}\exp(-g_{11}x^2-g_{22}y^2-g_{33}z^2),$$

the product of functions of x alone, y alone, and z alone. The probable error of $1/2g_{11}$ is identical with that of $a=[x^2]=1/n(x_1^2+x_2^2+\cdots+x_n^2)$, where n is the number of color matchings. Now, the probability, say $P(a)da$, of getting a value of $[x^2]$ within the range a to $a+da$ is

$$P(a)da=\text{const}\exp\Big(-g_{11}na\int dx_1dx_2\cdots dx_n\Big),$$

where "const" is independent of a (to be treated presently as our integration variable) and the integral is the volume of an n-dimensional spherical shell of inner radius $r=(na)^{\frac{1}{2}}$ and thickness $dr=1/2(n/a)^{\frac{1}{2}}da$. Apart from a constant numerical factor, this volume is $r^{n-1}dr$ or $a^{(n/2)-1}da$. Thus, we have

$$P(a)=C\exp(-g_{11}na)a^{(n/2)-1},$$

where C is independent of a. The value of this constant factor follows from the obvious condition

$$\int_0^\infty P(a)da=1,$$

which gives

$$C(g_{11}n)^{-n/2}\int_0^\infty u^{(n/2)-1}e^{-u}du=1$$

or

$$C=(g_{11}n)^{n/2}/\Gamma(n/2).$$

The function $P(a)$ is thus completely determined.

Now, the probable value of a itself is

$$[a]=\int_0^\infty aP(a)da=C\int_0^\infty a^{n/2}\exp(-g_{11}na)da$$
$$=\frac{C\Gamma(n/2+1)}{(g_{11}n)^{n/2+1}}=1/2g_{11},$$

and the probable value of a^2,

$$[a^2]=C\int_0^\infty a^{n/2+1}\exp(-g_{11}na)da=\frac{C\Gamma(n/2+2)}{(g_{11}n)^{n/2+2}}$$
$$=1/g_{11}^2n^2\frac{\Gamma(n/2+2)}{\Gamma(n/2)}=1/2g_{11}^2(1/2+1/n).$$

Whence

$$[a^2]-[a]^2=1/g_{11}^2(1/4+1/2n-1/4)=1/2ng_{11}^2,$$

so that

$$\text{P.E.}(a)=1/g_{11}(2n)^{\frac{1}{2}},$$

or

$$\text{P.E.}(1/g_{11})=1/g_{11}(2/n)^{\frac{1}{2}},$$

the announced formula. The required P.E. is thus inversely proportional to the *square root* of the number n of color matchings. Similarly, we have, of course,

$$g_{22}\text{P.E.}(1/g_{22})=g_{33}\text{P.E.}(1/g_{33})=(2/n)^{\frac{1}{2}}.$$

Acknowledgment

My thanks are due Mr. Walter R. J. Brown, of these Laboratories, for having drawn my attention to the errors in the original derivation of the formula.

II

To every covariant tensor g_{ik} corresponds a contravariant tensor g^{ik}, the *conjugate* or the *supplement* of g_{ik}. If D be the determinant of g_{ik} and D_{ik} its minors, the "supplement" is defined by

$$g^{ik}=D_{ik}/D=(\partial/\partial g_{ik})\log D.$$

And, what is important in the present connection, *the supplement of the supplement* is the *original tensor*, i.e., g_{ik} is the supplement of g^{ik}. This holds for any number of dimensions.

Now, the equations for the most probable g_{ik} derived from n free color matchings in the threefold are

$$(\partial/\partial g_{ik})(1/2\log D-ag_{11}-dg_{32}-dg_{23}-\text{etc.})=0,$$

where D is the determinant of the g_{ik}. Although the g_{ik} are known to be components of a symmetrical tensor, confusion and errors in the determination of the conjugate tensors can be best avoided by treating g_{ik} and g^{ik} as general, non-symmetrical tensors until the final results are obtained, when it can be recalled that $g_{ik}=g_{ki}$. Therefore, $1/2g^{11}=a$, etc., $1/2g^{23}=d$, $1/2g^{32}=d$, etc., or

$$g^{11}=2a,\ \text{etc.},\quad g^{23}=2d,\ \text{etc.},\quad g^{32}=2d,\ \text{etc.}\qquad(1)$$

This, then is the (most probable) *conjugate* colorimetric tensor g^{ik}, which may itself be useful (*viz.*, in writing down the equations of the color geodesics). Written out fully, the conjugate tensor is

$$g^{ik}=\begin{vmatrix} 2a, & 2f, & 2e \\ 2f, & 2b, & 2d \\ 2e, & 2d, & 2c \end{vmatrix}.\qquad(1)$$

The determinant of this tensor is

$$|g^{ik}|=8E=8\begin{vmatrix} a & f & e \\ f & b & d \\ e & d & c \end{vmatrix}.\qquad(1a)$$

Now, our required tensor g_{ik} is the conjugate of g^{ik}, that is to say,

$$g_{ik}=(\partial/\partial g^{ik})(\log E),$$

$$g_{11}=(bc-d^2)/2E,\quad g_{22}=(ca-e^2)/2E,\quad g_{33}=(ab-f^2)/2E,$$
$$g_{23}=g_{32}=(ef-ad)/2E,\quad g_{31}=g_{13}=(fd-be)/2E,\qquad(2)$$
$$g_{12}=g_{21}=(de-cf)/2E,$$

where, by (1a),

$$E=abc-(ad^2+be^2+cf^2)+2def.\qquad(2a)$$

We may note that the determinant $D=|g_{ik}|$, which may be needed in practice, is the reciprocal of $|g^{ik}|$, i.e.,

$$D=1/8E.\qquad(3)$$

The formulas (2) agree with solutions found and communicated to us by Mr. Anthony Marriage, of Kodak Ltd., Harrow, England.

The formulas (2) are much simpler than my original, incorrect formulas (16), Phil. Mag. 136 (February 1946), and in J. Opt. Soc. Am. **36**, 465 (1946).

Acknowledgment

My thanks are due Mr. Marriage for calling this matter to my attention and indicating the correct solution.

Whose Absorption Law?

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September 29, 1947

THE exponential law relating the absorptance of radiation to the thickness of the absorbing medium is attributed, especially in this country, to that great photometric pioneer, Johann Lambert, just often enough so that when a writer* ventures to attribute it to a predecessor, he is greeted with raised eyebrows and a demand that he make good his assertion. This has happened often enough to indicate that there may be some little interest in the genesis of this law.

The founder of the modern science of photometry was Pierre Bouguer (1698–1758), Royal Professor of Hydrography at le Havre. In 1729 he described his fundamental researches (a more extensive treatment was published posthumously in 1760) in a small 164-page book entitled *Essai d'Optique, sur la Gradation de la Lumiere.* He starts his first section with a proof of the inverse-square law and then describes briefly what is probably the first recorded photometric head with a halfway decent type of field. He then describes experiments on the reduction of the "force" of the light after being attenuated by various numbers of glass plates. The theoretical work of immediate interest appears in the second section of the book, and, for those who like their authority at first hand, let us note the pertiment passages from the copy in the library of this laboratory. On pages 44–45 we find, translating from the old French:

". . . now we must study the law according to which it [the light] diminishes in its passage [through transparent media]. One's first thought . . . is that if one imagines a transparent medium to be divided into parallel layers of equal thickness, all the layers will intercept the same number of rays, so that the light, receiving in the passage of each layer an exactly equal diminution, would decrease in arithmetical progression, . . ."

On the contrary, he had found that, if a certain pair of transparent plates reduced the intensity by 50 percent, a second pair did not reduce the intensity by an equal additional amount and thus produce extinction; indeed, he found that an appreciable amount of light was transmitted by even five such pairs. Returning to his theoretical argument, he points out that, if the second pair is to intercept the same number of rays, the same number must have been present originally, and then he continues (page 46):

"But since, at this layer, there may be present only a third or a quarter of the total number of rays, because all the others have already been interrupted, it is certain that this layer must also intercept three or four times fewer rays than the first. Thus the equal layers must not destroy equal quantities but only proportional quantities . . . it is evident that the light will always diminish in geometrical progression."

Apparently Bouguer was unfamiliar with the possibilities of the forty-year old method of fluxions in the present connection, but he knew, as he states on page 48, that the ordinates of a logarithmic curve vary in geometrical progression. For parallel rays, therefore, in his own words,

". . . les forces qu'a la lumiere, après avoir traversé differentes épaisseurs, peuvent être representées par les ordonnées d'une logarithmique qui a pour axe l'épaisseur du corps."

Translated,

". . . the intensity of the light, after traversing different thicknesses, can be represented by the ordinates of a logarithmic [curve] which has the thickness of the medium as its axis [of abscissae]."

Except that the inverse relationship is not stated explicitly, this is exactly the form that Lambert was to give later, as will be seen presently, and clearly entitles Bouguer to priority.

In 1760, two years after Bouguer's death, Johann Heinrich Lambert (1728–1777) published his opus entitled *Photometria, sive de Mensura et Gradibus Luminis, Colorum et Umbrae.* It has been translated into German by Anding and was published in 1892 as Nos. 31–33 of Ostwald's *Klassiker der exakten Wissenschaften* by Engelmann in Leipzig. Anding in his notes discusses Lambert's debt to his predecessors and admits on page 59 of Vol. III (No. 33) that Bouguer had discovered the exponential law although he had not expressed it in a concise form. Lambert himself frequently mentions Bouguer's work. Referring to the copy of *Photometria* in the Derr Collection of the Massachusetts Institute of Technology library, we find that Part V, Chapter I starts on page 388 as follows:

"§. 865. Both above [in present work] and more especially in the book of the famous Bouguer, which has been frequently quoted already, there occur many [passages] which lead to the determination of the weakening of light in transparent media, . . ."

On pages 390–1, Lambert derives the exponential law in the modern manner as follows, to use his own words:

"§. 875. Sit iam medium diaphanum CB (Fig. 79), lumen in istud incidat secundum directionem AB, sitque densitas incidentis = 1. Dum vero in P peruenit sit densitas residua = v, via percursa $AP = x$, spatiolum $Pp = dx$, densitas obstaculorum in hoc spatiolo = δ, debilitatio luminis ipsi debita = $-dv$, atque erit (§. 467.)

$$-dv = v\delta \cdot dx$$

adeoque

$$\log(1/v) = \int \delta dx.$$"

In English:

"§. 875. Let CB be the transparent medium, let the light fall on it in the direction AB, and let the intensity of the incident light equal unity. Now, when the light reaches P, let the remaining intensity be v, the path already traversed be x, the elementary layer Pp be dx, the density of the obstacles in this layer be δ [and] the diminution of the light caused by these obstacles be $-dv$; then we have

$$-dv = v\delta \cdot dx.$$

and, furthermore,

$$\log(1/v) = \int \delta dx.$$"

Lambert then goes on to point out that, if the elementary layers are equally thick (meaning apparently that their thickness is not a function of x), the last equation integrates into the familiar expression

$$\log(1/v) = \delta x.$$

A century later, August Beer made his contribution to the subject. To determine the exact nature and scope of this contribution, let us go to his paper in Poggendorff's Annalen **86**, 78–88 (1852), the title of which is "Bestimmung der Absorption des rothen Lichts in farbigen Flüssigkeiten." For his measurements, he used an outfit like the now familiar Martens photometer. After explaining the principle of the instrument, he defines absorption coefficient as the diminution (*Schwächung*) in amplitude that results from the traversing of a unit thickness of absorbing medium. Then on page 83 he points out that copper sulfate is chemically inert to water and continues

". . . first a tube one decimeter long was filled with a solution of copper sulfate which contained one volume of solution [having a] concentration of 13.5° [that is, which read 13.5° on his photometer] to nine volumes of water; the resulting solution thus had a dilution of 1/9 [10 percent concentration in modern terminology]. Another tube two decimeters long was filled with a solution of 1/19 dilution [5 percent concentration]. The

latter thus contains as much of the concentrated solution as the former; it also . . . showed in red light practically the same value for the angle α as the former. Specifically, the value of this angle for the short tube was 3°28′10″, for the longer 3°23′0″, which give for the absorption coefficient of the concentrated solution the approximately equal values 0.065 and 0.063."

In Beer's table on page 87, he records enough other examples to establish indubitably his law of the reciprocal relation between thickness and concentration. It is to be noted, however, that his law has nothing to do with Bouguer's exponential law and concerns the reciprocal relation between thickness and concentration alone, although he used Bouguer's law for his computations when necessary.

* For example, Arthur C. Hardy and Fred H. Perrin in *The Principles of Optics* (McGraw-Hill Book Company, Inc., New York, 1932), p. 24.

The Measurement of Strongly Reflecting Transmission Samples with the Commerical Recording Spectrophotometer

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October 27, 1947

THE recording spectrophotometer originated by Hardy,[1] and since made available commercially,[2] is so well known that no description is needed here. The photometric errors of this instrument have been treated by Pineo.[3] A very large error not mentioned by Pineo can occur, however, in the measurement of transmission samples which have a high specular reflectance. Outstanding examples are the recently developed interference filters which transmit a narrow region of the spectrum and reflect (instead of absorbing) the remainder.[4] These filters have the superficial appearance of excellent mirrors.

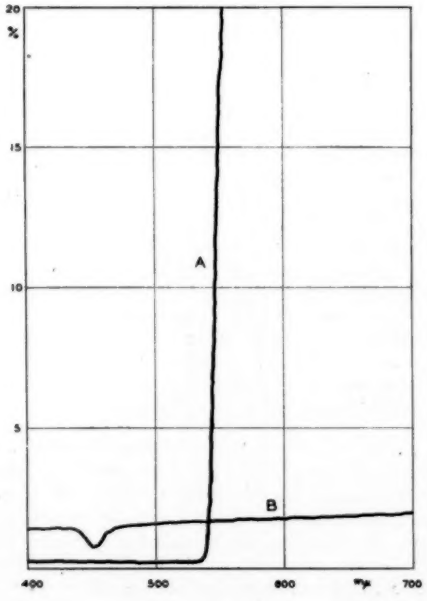

FIG. 1.

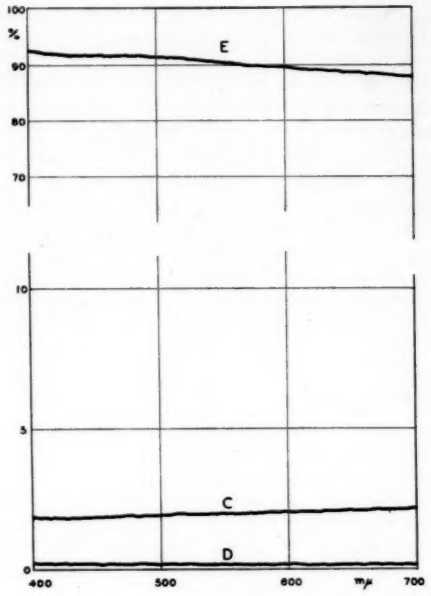

FIG. 2.

The error in question was drawn to the attention of the author by the extraordinary result shown in Fig. 1, which would have shaken one's faith in the rules of photometry if it had gone without explanation. Curve *A* of Fig. 1 shows the transmission of a sharp cut-off orange filter up to the point where it reaches 20 percent, and was made on the recording spectrophotometer with the 20 percent cam. Curve *B* shows the transmission of the same filter with an interference filter, having a maximum transmission of 28 percent at 452 mμ, placed in front of it. If the curves could be accepted at their face value, the interference filter would increase the transmission of blue light by the orange filter! It was further noticed that the values obtained for the interference filter alone were many times greater in the excluded regions of the spectrum than those obtained with a König-Martens spectrophotometer.

To investigate the source of this error, "transmission" measurements were made on a good first-surface aluminized mirror, provided with an opaque backing. Curve *C* of Fig. 2 shows the apparent transmittance of this completely opaque sample when placed in the transmission compartment against the wall in the usual position, i.e., normal to the beam. Curve *D* shows what happened when the mirror was slightly inclined so that no part of the reflected beam

struck the back of the decentered lenses of the spectrophotometer. The error was immediately seen to be due to reflection from the back of the decentered lenses, light from the sample beam being added to the reference beam. Since the photo-cell beneath the integrating sphere responds equally to light entering either aperture of the sphere, a fictitious reading of transmittance is obtained, varying a little with wave-length because the position of the beams changes slightly.

Curve *E* of Fig. 2 shows the reflectance of the mirror, compared with magnesium carbonate. This is about 50 times the apparent transmittance. It is quite evident that the spectrophotometer as supplied cannot be used to measure the transmittance of interference filters, but it should also be noted that even an ordinary filter, with a reflectance of between 4 and 8 percent, will add at least 0.1 percent to its true transmittance in this way.

The cure for this condition is to put a partition between the two beams, as was suggested by Pineo[3] on other grounds. This can be built into the telescoping tube between the decentered lenses and the transmission compartment if an index mark is put on the tube and on the lens support, although a small space will remain at the end of the tube nearest the integrating sphere.

[1] A. C. Hardy, J. Opt. Soc. Am. **25**, 305 (1935).
[2] J. L. Michaelson, J. Opt. Soc. Am. **28**, 365 (1938).
[3] O. W. Pineo, J. Opt. Soc. Am. **30**, 276 (1940).
[4] Supplied by Baird Associates, Inc., and by Farrand Optical Company, Inc.

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Utley, Don

Marion
Young, J. H.

Muncie
Sherry, John M.

Terre Haute
Howlett, B. A.

West Lafayette
Dull, Bernice B.
Menke, Warren W.

Whiting
Graves, Donald B.
Porsche, Francis W.

Winchester
Stump, Herman K.

IOWA—9

Ames
Carr, Percy H.
Kunerth, William
Wilhelm, Harley A.
Woodrow, Jay W.

Iowa City
Jahn, Theodore L.
Smith, Lothrop
Stewart, George W.
Tyndall, E. P. T.

Sioux City
Gwinn, Ira J.

KANSAS—1

Hays
Zinszer, Harvey A.

KENTUCKY—4

Fort Knox
Horsfall, R. Bruce, Jr.

Louisville
Goodman, James S.
Nisbet, D. F.
Zaremba, Vitto Stephen

LOUISIANA—3

Baton Rouge
Tenney, Horace M.

New Orleans
O'Connor, Robert T.
Schales, Otto

MAINE—4

Orono
Bennett, Clarence E.
Crofutt, Charles B.

South Paris
Hall, Charles G.

Waterville
Brown, Sherwood F.

MARYLAND—57

Aberdeen Proving Ground
Perry, James W.

Baltimore
Andrews, Donald H.
Bartlett, Neil R.
Barton, Vola Price
Beck, William Henry
Beidler, Lloyd M.
Bellamy, Blanche R.
Bialecki, Adolph
Dieke, G. H.
Friedenwald, J. S.
Larkin, Charles R.
Lentz, Charles H.
Macht, David I.
Peters, C. W.
Pfund, A. H.
Reed, J. D.
Reimann, Genevieve B.
Rowland, William M.
Scholz, Louis A.
Sloan, Louise L.
Strong, John
Talbot, Samuel A.
Wood, R. W.

Bethesda
Draeger, R. H.
Gould, Wendell O.
Washer, Francis E.

Chevy Chase
Brackett, Frederick S.
Douglas, Charles A.
Gardner, I. C.
Kennard, Ralph B.
Maxwell, Louis R.
Smith, Francis A.
Wensel, H. T.

College Park
Morgan, Raymond
Slavin, Morris

Hyattsville
Armstrong, David W.
Davis, Russell E.
Myers, Alfred T.

Peterson, Maurice J.
Saylor, Charles Proffer

Kensington
Creitz, E. Carroll
Schroeder, Jacob

La Plata
Johnson, Lyle T.

Lanham
Scofield, Francis

Riverdale
Hechmer, Elizabeth A.

Silver Spring
Barthel, C. E., Jr.
Byers, Robert C.
Carl, Howard F.
Lovins, Gerald H.
Ramsay, Bertrand P.
Silverman, Shirleigh
Unger, Hilbert J.
Wilkie, John B.

Takoma Park
Ryan, Charles E.

Texas
Kelly, Kenneth L.

Towson
Perry, Wilbur H.

Westminister
Summers, R. D.

MASSACHUSETTS—156

Amherst
Soller, Theodore
Stifler, W. W.

Arlington
Carey, Charles A.
Lanza, Carmelo

Attleboro
Peterson, Arthur W.

Bedford
Harrison, J. R.

Belmont
Guiney, John J.
McFee, Raymond

Beverly
Gibb, Thomas R. P., Jr.

Boston
Burian, Hermann M.
Davis, Harry Floyd
Forbes, Alexander
Gillis, Ronald C.
Greenwood, Willard P.
Macdonald, Duncan E.
McFarland, Ross A.
Merritt, Thomas P.
Niven, Jorma I.
Rines, David
Smith, William
Stark, Stephen W.
Welch, George B.

Brookline
Cohen, Joseph H.
Ehrenfried, George
Jordan, Joseph, Jr.
Vigo, Samuel
Williams, Philip H.

Cambridge
Accardo, Carl A.
Baird, Walter S.
Beaman, E. O.
Berggren, Jane L.
Bickford, L. R., Jr.
Billings, B. H.
Blout, Elkan R.
Carpenter, Robert O'B.
Compton, Karl T.
Dudley, Beverly
Duntley, Seibert Q.
Dusedau, Edwin W.
Eastham, Melville
Eaton, S. Edward, Jr.
Federer, Charles A., Jr.
Finch, Rogers B.
Furnas, Thomas C., Jr.
Gardner, Edward E.
Hardy, Arthur C.
Harrison, George R.
Harvey, George G.
Haskell, Stanley W.
Hyde, W. Lewis
Jones, R. Clark
Keuper, Jerome P.
Krasner, Paul R.
Land, Edwin H.
Loofbourow, John Robert
Lord, Richard C.
Lyman, Theodore
Moon, Parry
Morse, Richard S.
Mueller, Hans
Nottingham, Wayne B.
Oldenberg, Otto
Perkins, Willis D.
Petersen, Max
Polaroid Corporation
Pope, Arthur
Power, John W.
Pulling, Nathan H.
Rosenblum, Louis
Rule, John T.
Sable, Arthur J.
Saxenian, Hrand
Schwarz, Edward R.
Sears, Francis W.
Sterner, John
Stockbarger, Donald C.
Terrio, Barbara W.
Wald, George
Wasserstein, B.
Whitney, Joy Gordon
Wrigley, Walter
Zulon, John Anthony

Chestnut Hill
Dunham, Theodore, Jr.

Cohasset
Dean, Russell
Manahan, Paul R.

Concord
Parke, N. Grier, III

Dodge
Gunter, Roy Chalmers, Jr.

Dorchester
Tytell, Boris H.

Duxbury
Bittinger, Charles

East Dedham
McNally, J. Rand, Jr.

Everett
Kelly, Joseph B.

Franklin
Sampson, Donald K.

Greenfield
Wing, Howard E.

Harwichport
Sawyer, Harold E.

Ipswich
Norman, Daniel
Wylie, Robert R.

Lawrence
O'Neil, Frank J.

Lenox
Ashley, Samuel Ed. Q.

Lexington
Schecter, Harry
Schneider, Edwin G.

Lincoln
Mann, David W.

Malden
Anderson, James C.
Frost, Eugene N.
Mayne, Robert H.

Manchester
Brynes, Kermit

Marblehead
Gray, S. M.

Mattapan
Bavley, A.
Hargreaves, Walter A.

Medford
Ballard, Stanley S.
Smith, Charles G.

Needham
Stetson, Harlan T.

Newton
Merrill, Dwight P.

Newton Centre
Amann, Rudolf
Ellis, Frederick W.

Newton Highlands
Spike, J. E., Jr.

Newtonville
Law, William S.

North Brookfield
Cooke, Frank

Northampton
Anslow, Gladys Amelia
Mohler, Nora May

Norton
Shook, G. A.

Pittsfield
Fitz, Elmore J.

Quincy
Young, F. Mansfield

Randolph
Reed, Allan W.

Salem
Butler, Keith H.
Levesque, Henry J.
Quinn, John E.
Rentoumis, George M.

Somerville
Steiger, W. R.

South Hadley
Allen, Mildred
Carr, Emma P.

Southbridge
American Optical Company
Boeder, Paul
Davis, John K.
Glancy, Anna E.
Haynes, Paul H.
Rowe, Louis F.
Tillyer, Edgar D.
Wells, John M.

Springfield
Ingle, George W.

Sturbridge
Herman, William F.

Waban
Baker, James G.
Jarrell, Richard F.

Watertown
Kent, Rockwell, III

Wellesley
Griggs, Mary A.
McDowell, Louise S.
Zigler, Michael J.

Wellesley Hills
Davis, Richard H.

West Springfield
Walrath, E. K.
Weston
Miley, H. A.
Thomas, Alexander
Williamstown
Burnham, John
Crawford, F. H.
Woods Hole
Klebba, Arthur A.
Worcester
Burns, William F., S. J.
Lucas, Ernest H.
Parker, Allan E.

MICHIGAN—63

Ann Arbor
Argus Incorporated
Blackwell, H. Richard
Boyd, Robert A.
Enns, J. H.
Feder, Donald P.
French, Hobert W., Jr.
Harvey, James E.
Kraus, Edward H.
Lucht, Vivian M.
Meyer, Charles F.
Randall, H. M.
Sawyer, Ralph A.
Sleator, W. W.
Williams, Robley C.
Wolfe, Ralph A.
Battle Creek
Beohm, E. E.
Hoyt, Gordon D.
Berkley
Fry, David L.
Dearborn
Bryan, Ford R.
Tuttle, Henry A.
Detroit
Boyd, Bernard R.
Brandt, Stanley M.
Canning, Robert A.
Dietert, Harry W.
Edgar, William J.
Goodman, Hyman
Hulbert, Henry S.
Hull, L. J.
King, Carl
Lamb, Frances W.
Mueller, Alexander
Nahstoll, George A., Jr.
O'Neill, W. R.
Poetker, Albert H., S.J.
Rassweiler, Gerald M.
Schuch, John
Vaile, C. A.
Vergbo, Joseph C.
White, M. M.
East Lansing
Bartley, S. Howard
Ewing, Dwight T.
Flint
Hoagbin, Joseph E.
Grand Rapids
Neeland, Gerald Kent
Kalamazoo
McGonnagle, Warren J.
Rood, Paul
Midland
Graham, Joseph P.
Grossman, Harold H.
Hess, T. M.
Matheson, Lorne A.
Peterson, R. E.
Reinhardt, Lyle Gordon
Saunderson, Jason Lewis
Ullrey, Mark A.
Wright, Norman
Muskegon
Gruszecki, Peter J.
Hesling, Francis M.
Sampson, A. M.
Pontiac
McMath, Robert R.
Willow Run
Langley, Frank P., Jr.
Neill, Howard W.
Niles, John R.
Wyandotte
Beyer, Karl W.
Boettner, Edward A.

MINNESOTA—15

Duluth
Banning, Mary
Minneapolis
Anderson, Albert L.
Braden, John
Buchta, J. W.
Crawford, Bryce L., Jr.
Kliever, Waldo H.
Meehan, E. J.
Stenstrom, Wilhelm
Tate, John T.
Valasek, J.
Northfield
Hetle, E.
Rochester
Ogle, Kenneth N.
Sheard, Charles
St. Paul
Rubens, Sidney M.
Wayzata
Brueske, George A.

MISSOURI—18

Columbia
Reese, Herbert M.
Smith, Eastman
Joplin
Amthauer, Earl W.
Carls, Robert J.
Kansas City
Trimble, Frank H.
Ziegler, George E.
Normandy
Field, Byron D.
St. Louis
Bubb, Frank W.
Compton, A. H.
Mather, Keith B.
Merle, John, Jr.
Meyer, H. Sigmund
Ruehle, A. E.
Schepler, Herman C.
Skeffington, Mary Jane
Sappington
Cobb, Percy W.
Springfield
Burns, Loren V.
Webster Groves
Munch, Ralph H.

NEBRASKA—3

Lincoln
Jensen, J. C.
Omaha
Hayden, Charles K.
Spieth, Howard H.

NEW HAMPSHIRE—11

Durham
Daggett, Albert Frederick
Howes, Horace L.
Exeter
Little, E. P.
Hanover
Ames, Adelbert, Jr.
Babbitt, Ethel Jean
Campbell, Clarence J.
Dimitroff, George Z.
Gliddon, Gordon H.
Karwoski, Theodore F.
Proctor, Charles A.
Triller, Wendell

NEW JERSEY—104

Bloomfield
Beggs, Eugene W.
Eichner, L. C.
Rentschler, Harvey C.
Bound Brook
Abbott, Ruth
Buc, George L.
Royer, George L.
Stearns, Edwin I.
Zinzow, William August
Caldwell
Rudolph, Hellmuth C.
Rugg, Frank M.
Camden
Maloff, Ioury G.
Carteret
Ernst, Runyon G.
Chatham
Herriott, William
East Orange
Aster, Alvin K.
Hillman, Conway D.
Hodge, Percy
Elizabeth
Weinhart, Howard W.
Englewood
Wood, Francis Carter
Fair Lawn
Campbell, H. N.
Clutz, Claude S.
Garland, Daniel L.
Glen Rock
Ball, G. Milton
Van Dien, J. Edward
Grasselli
Lord, Bradley
Hackensack
Siganowick, John

Haddonfield
Sachtleben, Lawrence T.
Harrison
Guettel, Charles L.
Power, A. D.
Highlands
Weiss, Richard A.
Hoboken
Hawkes, John B.
Keuffel, Carl W.
Keuffel & Esser Company
Jersey City
Blackham, Wilfrid
Kearny
Austin, J. B.
Lafayette
de Vries, Ralph E.
Long Branch
Kaprelian, Edward K.
Manville
Miller, M. C.
Maplewood
Hazeltine, Alan
Margate City
Winnek, Douglas Fredwill
Merchantville
Patterson, J. Edward
Millington
Goodwin, William J.
Montclair
Hudson, Richard D., Jr.
Murray Hill
Jaycox, Edwin K.
Molnar, Julius P.
New Brunswick
Coy, Nettie H.
Noebels, Henry J.
Newark
Anderson, William T., Jr.
Balamuth, Lewis
Bleiweiss, Arthur F.
Hamlin, John R.
Laufer, Jerome
Lincoln, Arnold J.
Ranger, Richard H.
Schweizer, Ernest
Newton
Houskeeper, William G.
Potter, Rowland S.
Nutley
Howland, Walter A.
Oaklyn-Audubon
Edmund Salvage Company
Parlin
Conklin, O. E.
Passaic
Gibbons, W. A.
Hampton, Robert R.
Lampman, Moreon E.
Monego, J. Constantin
Wilber, David T.
Paulsboro
Socony-Vacuum Laboratories
Perth Amboy
McLellan, Roy D.
Pequannock
Sherrer, Warren A.
Phillipsburg
Larsen, E. C.
Plainfield
North, Charles H.
Stilwell, G. Raymond
Princeton
Chase, Aurin M.
Epstein, David W.
Foss, Carl E.
Furman, N. Howell
Leverenz, H. W.
Shenstone, Allen G.
Sziklai, George C.
Rahway
Farnsworth, Marie
Loofbourow, Rodger W.
Swindells, Frank E.
Red Bank
Green, Milton
Ridgefield
Geier, George
Ridgewood
Hill, Lyman P.
Moffitt, G. W.
Short Hills
Davisson, C. J.
Somerville
Watson, John G.
South Amboy
Jacobsen, Arthur E.
South River
White, Deane R.
Summit
Farr, Wanda K.
Stevens, B. Vincent
Wehe, H. G.
Trenton
Pehta, Arnold John
Upper Montclair
Arnott, Edward G. F.
Ives, Herbert E.
Webber, Alfred C.
Verona
Wyckoff, Norman W.
Watchung
Woods, John T.
West Englewood
Walton, John F.
Westfield
Gray, Arthur W.
Read, Harry Stafford
Wiley, S. Richard
West Orange
Edison, Theodore M.
Fogle, Marlin E.
Woodbury
Hochgesang, Frank P.

NEW MEXICO—7

Albuquerque
Karrer, S.
Martin, Guy V.
Los Alamos
Holland, Thomas Edwin
Marling, John B.
Santa Fe
Porter, Eliot F.
Smith, I. Lee
Sullivan, H. C.

NEW YORK—466

Albany
Crowe, M. O'L.
Rankin, Charles W.
Waldbauer, Louis J.
Walker, Amy
Amsterdam
Hanlon, John J.
Perry, John E.
Arverne
Kramer, Milton J.
Athens
Hallock, Herbert B.
Beacon
Cummings, C. E.
Beechhurst
Marks, Alvin M.
Binghamton
Arnold, Paul
Bingham, Ronald H.
Bunce, Lois S.
Current, Ira B.
Dick, Jane Blaikie
Harsh, Harold C.
Hoerlin, Hermann
Keables, Marion E.
Knop, Victor R.
Lenz, Lester R.
Morreall, H. W., Jr.
Sweet, Monroe Hamilton
Tiedeman, John A.
Bronx
Doller, Samuel
Hett, John H.
Newman, Seymour
Bronxville
Greene, Bernard F.
Brooklyn
Bernstein, Harry S.
Chalupski, Victor
Chikofsky, S.
Davis, George W. C.
Day, George
Dunn, E. J., Jr.
Eaton, William W.
Engel, W. H.
Engelson, Howard R.
Friedman, Harry S.
Grace, Frank E.
Harris, Lawrence
Heitzmann, Janet Fuller
Hughes, Harold Kenneth
Isaacson, Leon D.
Johnston, Elizabeth
Kaplowitz, Morris
Lawson, W. L.
Levine, Louis
Maerz, A.
McGreevy, Joseph M.
Means, J. A.
Parker, William L.
Parsegian, V. L.
Pincus, Leo I.
Rauch, Seymour
Rosenberg, Ben
Schwarzschild, Myron M.
Stevens, E.
Stone, Florence M.
Buchanan
Wurzburg, F. L., Jr.
Buffalo
Barton, Charles W.
Bennett, Alva H.
Brown, Morden G.
Cohen, Ernest
Elden, Richard E.
Ford, James W.
Fosbury, Francis J.
Kavanagh, Arthur J.
Meloon, D. T.
Meyer, Edgar J.
Muller, Robert M.
National Aniline Division

Osterberg, Harold
Peck, William F.
Reardon, Joseph D.
Ripley, D. L.
Small, John H.
Webster, Gilbert E.

Canton
Smith, John F.

Corning
Cartwright, C. Hawley
Corning Glass Works
Erickson, A. Alfred
Gage, H. Phelps
Lillie, Howard R.
Littleton, Jesse T., Jr.
Parker, Charles J.
Sheldon, John L.
Smith, Gail Preston
Werner, Alan J.
Wetmore, Warren L.

Corona
Tralli, Nunzio

Crompond
Sharo, Ernest

Elmhurst
Braun, Ben
Eckweiler, Howard J.
Kollsman Instrument Division

Elmira
Kelly, James H.
Stong, Guy E.

Endicott
Malmros, Alf

Flushing
Oszy, Alexander J.

Forest Hills
Bechtold, Edwin W.
Rosett, Bernard

Garden City
Bronson, S. Davis

Geneva
Haussmann, Alfred C.
Spengler, John A.

Great Neck
Lighty, Paul E.

Grymes Hill
Lindemann, Howard C.

Hamilton
Gleason, Paul R.

Hamburg
Jackson, Trumbull Starr

Hempstead
Faurote, Richard B.
Grosch, Herbert R. J.

Hilton
Snitchler, L. Clyde

Hollis
Zieler, Hans Wolfgang

Honeoye
Sundeen, Earl I.

Huntington Station
Tuttle, Clifton M.

Irvington
Duffendack, O. S.
Schaffers, T. W. M.

Ithaca
Cohen, Jozef
Cottrell, Casper L.
Fogelsanger, Aldus
Gartlein, Carl W.
Grantham, G. E.
Merritt, Ernest
Murdock, Carleton C.
Shaw, R. William

Jackson Heights
Harrison, David P. (Mrs.)
Monahan, Thomas I.

Jamaica
Ellis, S. B.
Fairchild Camera & Instrument Corporation
Tocher, Ralph B.

Johnson City
Friedman, Joseph S.
Judkins, Stanley L.
Ketcham, Henry C.

Kenmore
Gillette, R. H.

Kew Gardens Hill
Liben, William

Limestone
Pfister, Rudolf J.

Lockport
Magrun, William H., Jr.
Windle, Maurice L.

Long Island City
Ainsworth, George
Hellige, Peter W.

Lynbrook
Dixon, Leslie G.

Malverne
Winter, Martin H.

Manhasset
Bitner, Ralph E.
Carbonara, Victor E.

Mineola
Rattray, George

Mt. Kisco
Blake, Edwin M.
Fisher, Harold M.

Mt. Vernon
Brown, Earle B.
Hineline, Harris D.
Wetzel, Reinhard A.

New Rochelle
Portman Machine Tool Company

New York
Amdursky, Mark Ernest
American Cystoscope Makers, Inc.
Bannon, Robert E.
Barton, Henry A.
Bastien, Roy C.
Bell, R. H.
Bell Telephone Laboratories, Inc.
Beller, William C.
Bentley, Edward P.
Berens, Conrad
Birren, Faber
Boch, Alfred
Bragg, H. E.
Carlsen, Conrad P.
Century Lighting, Inc.
Chace, Robert R.
Cloud, J. L.
Davis, Bergen
Dollmann, Elsie M.
Dolton, Dorothy
Draves, Carl Z.
Dreyfuss, R. M.
Dunn, Gano
Failla, G.
Farrand Optical Company, Inc.
Farwell, H. W.
Ferguson, W. F. C.
Ferrari, C. G.
Finkelstein, Isidore S.
Fish-Schurman Corporation
Fread, Bernard
Gardner, William A.
Gnorich, W.
Goldmark, Peter C.
Goldsmith, Alfred N.
Graham, C. H.
Graham, Robert E.
Greenleaf, Allen R.
Grimson, Samuel B.
Gristle, Murray L.
Hardy, J. D.
Hardy, LeGrand H.
Hartmann, Werner
Haynes, N. M.
Hebo, Halfdan
Henninger, John H.
Hillyer, Curtis
Hoke, Charles Hearn
Holst, W. A.
Interchemical Corporation
Kashdan, William H.
Kingsbury, Edwin F.
Krewer, Semyon E.
Leventhal, J. F.
Little, William F.
Luneberg, Rudolf K.
Macbeth, Norman
Martin, Alfred E.
Mauersberger, Herbert R.
Maurer, John A.
Millar, Preston S.
Miller, Osborn M.
Munsell, A. E. O.
Muscat, Lewis
Newcomer, H. Sidney
Pajes, Wolf S.
Palmer, M. W.
Paul, M. Rea
Pavelle, Leo
Pearson, Frank A.
Pegram, George B.
Rand, Gertrude
Reilly, Frank J.
Reynolds, F. W.
Rittler, M. Catherine
Rohrbaugh, John H.
Rolph, Thomas W.
Roots, Yale Kirby
Rosin, Seymour
Schaffner, Frederick Q.
Scheick, J. A.
Schmid, Fred
Schurman, Ferdinand
Shillaber, Charles P.
Smith, Daniel
Smolar, Murray M.
Speyer, Edward M.
Stein, Eugene
Treleaven, Clifford L.
Tyler, John E.
Varden, Lloyd E.
Webb, Harold W.
Wertenbaker, Clark
Williams, E. C.
Williams, Horatio B.
Wolff, R. I.
Wormser, Eric M.

Niagara Falls
Curtis, J. Alfred
Forgeng, William D.
O'Leary, William J.
Trusler, H. F., Jr.

Norwich
Ells, Victor R.
Paul, Henry E.

Oceanside
Urbanik, John G.

Oneida
Iredale, John R.

Oneonta
Micco, L. A.

Orangeburg
Mitteldorf, A. J.

Ontario
Peterson, Lee
Ozone Park
Babish, Richard
Painted Post
Gage, O. A.
Palisades
Cooley, J. P.
Pelham Manor
Darby, Hugh H.
Pittsford
Covell, William D.
Pleasantville
Berger, F. B.
Garman, R. L.
Point Pleasant
Perkins, Willard T.
Port Washington
Davidson, Ward F., Jr.
Rochester
Abel, Irving R.
Aklin, George H.
Alexander, C. H.
Altman, Fred E.
Anderson, James M.
Bancroft, George Herbert
Bausch, Carl L.
Bausch & Lomb Optical Company
Benford, James R.
Bennett, Harold F.
Benson, Bernard
Bishop, Fred M.
Blum, Albert H.
Brant, Margaret
Britton, William C.
Brockway, Ellsworth M.
Brown, Fordyce M.
Carroll, Burt H.
Cary, Donald S.
Castle, John, Jr.
Chambers, Gordon A.
Chesna, John
Clapper, F. R.
Clark, Janet H.
Cleveland, H. W.
Coles, Harold W.
Colton, Howard C.
Condit, Harold R.
Cook, Alan A.
Craig, William M.
Crewdson, E.
Dakin, Ralph K.
Day, Carl A.
Debenham, Jack K.
Dessauer, John H.
Eastman Kodak Company
Eisenhart, M. H.
Ellestad, Gerhard A.
Epstein, L. Ivan
Evans, Charles H.
Evans, John C.
Evans, Ralph M.
Fitter, Charles F., Jr.
Flint, Edward F., Jr.
Forrest, John W.
Fortmiller, Louis J.
Foster, Leon V.
Fowler, Richard Crosman
Friar, Lawrence B.
Graeper, Walter W.
Gramm, Charles F.
Greppin, Ernest H.
Hanson, W. T., Jr.
Harper, David C.
Hawley, Mones E.
Herzberger, Max
Hickman, Kenneth C. D.
Higgins, George C.
Hoadley, H. Orlo
Hodge, Edwin S.
Holmes, F. M. Emerson
Hopkins, Robert E.
Hudson, Lena M.
Hurvich, Leo M.
Ingalls, Arthur L.
Jameson, Dorothea
Jelley, Edwin E.
Jobe, Frederick W.
Johnson, Gerald A.
Jones, Frank L.
Jones, L. A.
Kadesch, Robert R.
Kanwisher, John
Kaplan, Burton
Kingslake, Rudolf
Kisner, Walter I.
Koch, Donald A.
Kottler, Friedrich
Kreidl, Norbert J.
Krolak, Leo J.
Kurtz, Henry F.
Kurtz, John C.
Leurgans, Paul J.
Levin, Aaron A.
Litten, Walter
Loveland, Roger P.
Lowry, Earl M.
MacAdam, David L.
Magill, Lincoln C.
Magliozzi, Joseph
Marks, Jerold S.
McAlister, E. D.
McFarlane, John W.
McLeod, John Henry
Mees, C. E. Kenneth
Miller, Oran E.
Milligan, Francis H.
Milne, Gordon Gladstone
Minkler, Marcus W.
Morey, D. R.
Morris, Robert H.
Morrison, Charles A.
Murray, Allen E.
Nail, Nelson R.
Nelson, C. N.
Neumer, Arthur E., Jr.
Newhall, Sidney M.
Newhouse, Herman
Nitchie, Charles C.
Nixon, Ivan L.
Nurnberg, C. R.
O'Brien, Brian
O'Grady, E. John
Orser, W. Donald
Ott, Harry G.
Overhage, Carl F. J.
Perrin, Fred H.
Pestrecov, Konstantin
Phillips, Sheldon
Pickering, R. D.
Platt, Joseph B.
Polster, Harry D.
Putnam, Thomas E.
Reid, Charles D.
Reiss, Max
Reynolds, Leon M.
Richardson, David
Richardson, Earle E.
Rogers, Harry L., III
Roos, Paul A.
Rouvina, James
Russell, Marion E.
Sandvik, Otto
Schade, W. E.
Scharf, Philip T.
Schoen, Arthur L.
Scott, Murray R.
Shurkus, Albert A.
Silberstein, Ludwik
Smith, John H.
Smith, Warren J.
Staud, Cyril J.
Steadman, Luville T.
Steiner, Oscar
Stevens, Paul W.
Stich, Jules N.
Straat, Harold William
Stultz, Keith F.
Swann, William F.
Tackaberry, R. B.
Taylor, Edward J.
Taylor, Joseph F.
Tolle, Karl
Trivelli, A. P. H.
Tupper, John L.
Turner, A. Francis
Uhle, Otto D.
Ullrich, O. A.
Urbach, Franz
Walker, Robert C.
Walton, Sam F., Jr.
Watson, James S., Jr.
Weaver, Karl S.
Webb, Julian H.
Wightman, E. P.
Williams, David L.
Williams, Franklin G.
Wilsey, Rex B.
Wing, Albert B.
Wolfe, Robert N.
Wood, Donald L.
Wooters, Glenn C.
Rome
Schatz, Frederick V.
St. Albans
Fairchild, Charles O.
St. Bonaventure
Organ, Thomas J.
Sullivan, Francis J., O.F.M.
Saratoga Springs
Strock, Lester W.
Schenectady
Barnes, Norman F.
Benford, Frank
Blodgett, Katharine Burr
Dushman, Saul
Hupman, George H.
Jacobson, Woodrow R.
Koller, Lewis R.
Michaelson, J. L.
Rice, Chester W.
Studer, Frank J.
Tobin, Bernard
Snyder
Sharp, Howard M.
Suffern
Frachtman, Henry
Syracuse
Mader, William A.
Oplinger, George
Warntz, Adrian L.
Thompkinsville
Brock, Frederick W.
Troy
Carragan, G. Howard
Gurley, W. & L. E.
Wellsville
Broadhead, D. T.
White Plains
Longwell, Frederick P.
Yonkers
Arthur, John M.
Ashcroft, A. Griffin
Flory, Louis Paul

NORTH CAROLINA—4

Charlotte
Palmer, Roy. A.
Enka
Jolliff, E. Corwith
Paw Creek
Elting, John P.
Raleigh
Birkel, George, Jr.

OHIO—103

Akron
Dunderman, Frank V.
Harris, Clyde W.
Householder, F. F.
Barberton
Marks, Maurice E.
Bedford
Emery, Frederic H.
Canton
Vance, E. R.
Cincinnati
Balinkin, Isay A.
Boegli, Charles P.
Cholak, Jacob
Coffin, Allen
Dreyer, John F.
Rosevear, F. B.
Sperti, George S.
Cleveland
Adams, Elliot Q.
Bedell, Howard M.
Buchele, Donald
Buck, G. B., Jr.
Cameron, Donald B.
Craig, Russell M.
Ditchman, J. P.
Easley, M. Adelaide
Frederick, G. William
Hale, Danforth R.
Harrington, Pauline P.
Harrington, Roger E.
Hodgman, Charles D.
Hoover, Paul L.
Hutchisson, Elmer
Jones, Matthew T.
Luckiesh, M.
Lundin, C. A. Robert
Meese, G. E.
National Carbon Company
Rozsa, J. T.
Sackett, J. Warren
Shankland, Robert S.
Spencer, Charles Douglas
Sutton, Allen M.
Taylor, A. Hadley
Columbus
Balcom, Margaret M.
Bridgman, C. S.
Brode, Wallace R.
Chapman, James M.
Chapman, Robert M.
Fry, Glenn A.
Hesthal, C. E.
Hofstetter, Henry W.
Knoll, Henry A.
Oetjen, Robert A.
Pickett, Edward E.
Ramaley, Edward J.
Renshaw, Samuel
Russell, Howard W.
Stone, Conrad A.
Woods, Frank R.
Cuyahoga Falls
Schultz, H. A.
Dayton
Brocklehurst, R. E.
Burka, Samuel M.
Gard, Orin P.
Katz, Amrom H.
Koch, Wendell R.
Lapenas, Torp A.
Mohn, Olof
Nierenberg, Richard N.
Univis Lens Company
Woodford, Edward B.
East Cleveland
Barnes, Bentley T.
Forsythe, W. E.
Lamb, Robert E.
Reuter, Frederic W., Jr.
Thayer, Richard N.
Elyria
Windsor, Manly M.
Euclid
Poritsky, Abraham
Ricksecker, R. E.
Fostoria
Lozier, W. Wallace
Zavesky, Robert J.
Kent
Halverson, Gilbert
Lorain
Kalischer, P. R.
Marietta
Phillips, Thomas D.
Middletown
Steakley, W. E.
Woodruff, J. F.
Newark
Waggoner, Jack H.
North Canton
Holl, Nevin S.
Osborn
Pryor, Paul L.
Oxford
Billhartz, William H.
Painesville
Wilson, Mabel F.
Ravenna
Ballard, James W.
Shaker Heights
Gitson, Leonard J.
Toledo
Coady, George F.
Dunipace, Donald W.
Kiser, M. G.
Lutz, Fred W.
McMaster, Harold A.
Powell, H. Eugene
Sharp, Donald E.
Shuck, Lowell M.
Switzer, M. H.
Van Zee, Arthur F.
Vincent, Harvard B.
Warren
Baxter, R. C., Jr.
Lab, Roy F.
Wooster
Sayre, J. D.
Yellow Springs
Knorr, H. V.

OKLAHOMA—7

Bartlesville
Fast, Edwin
Rall, Harry T.
Thornton, Vernon
Enid
Mitchell, Donald E.
Norman
Charles, George W.
Nielsen, J. Rud
Tulsa
Silverman, Daniel

OREGON—5

Corvallis
Garman, John C.
Weniger, W.
Eugene
Paul, Frederick William
Portland
Ellickson, Raymond
Orr, James M.

PENNSYLVANIA—137

Abington
Decker, John C., Jr.
Allentown
Simpson, S. F.
Bethlehem
Bayley, P. L.
Clark, Albert, Jr.
Horscroft, W. Frank, Jr.
Irish, Paul R.
Serfass, Earl J.
Bristol
Hoffman, Charles W.
Bryn Mawr
Helson, Harry
Chadds Ford
Rossmassler, Selma
Chambersburg
Weeks, Dorothy
Creighton
Chess, James S.
French, Preston W.
Lytle, W. O.
Morris, Paul R.
Parker, Henry F.
Vine, Benjamin H.
Donora
Beckley, Hugh
Drexel Hill
Scott, W. E.
Duquesne
Dunn, Edward J.
East Pittsburgh
Coles, Donald K.
Easton
Busse, Warren P.
Godlove, I. H.
Hemmendinger, Henry
Larson, Ernest T.
Lonergan, Ann
McQuarrie, W. C.
Erie
de Witt, Wallace
Hutchison, Jack D.

Exton
Chandler, Alfred B.
Fort Washington
Theel, Percival
Grampian
Moore, William R.
Greensburg
Curran, James J.
Harmarville
Russell, R. G.
Harrisburg
Wells, Franklin H.
Industry
Oshry, Howard I.
Lancaster
Brunner, Adolphus J.
Glover, Alan N.
Robinson, Howard A.
Latrobe
Heid, Roland L., O.S.B.
McKeesport
Kruper, A. P.
Narberth
Tabor, Lewis P.
New Kensington
Bishop, F. L., Jr.
Churchill, J. R.
Norwood
Rosenbaum, E. J.
Palmerton
Barnett, C. E.
DeVore, J. R.
Philadelphia
Adler, Francis Heed
Applegate, C. E.
Bamford, Harry S.
Blitzstein, William
Bloomsburgh, Ralph A.
Boydston, R. W.
Brice, Brooks A.
Bronk, Detlev W.
Castor, LaRoy N., Jr.
Chwalow, Morton L. E.
Cornog, I. Clyde
Crampton, George S.
Drabkin, David L.
Duncan, Ralph W.
Edelman, Norman B.
Fastie, W. G.
Gamson, William
Harrison, T. R.
Hartline, H. Keffer
Ildstad, Reidar
Jaggard, George
Kaspereit, Otto K.
Koenig, Bernard R.
Kraft, Frank Robert
Lisan, Philip
Machler, Raymond Charles
Morse, Mark P., Jr.
Peckham, R. H.
Pesce, Mario R.
Pfluger, Catherine F.
Schaeffer, W. H.
Sherman, Jacob
Shreve, O. Davis
Spiegel-Adolf, Mona
Stevens, Ludlow R.
Stewart, Thomas S.
Stroupe, James D.
Taylor, George
Thomas, Arthur H., Company
Whitney, Will A.
Witmer, Enos Eby
Woodman, J. F.
Pittsburgh
Allen, Alexander J.
Ashe, Frank C.
Foote, Paul D.
Francis, C. B.
Friedel, Robert A.
Marston, Alfred L.
Martin, William H.
Moreland, Ben A.
Pitzer, L. E.
Ruhe, Carl
St. Peter, Wilfred N.
Seitz, Frederick
Slish, Michael
Stapsy, Irving S.
Strasser, Alexander
Taylerson, Ewart S.
Tillotson, E. Ward
Venable, William Mayo
Warga, Mary E.
Work, Harold K.
Worthing, A. G.
Pottstown
Kepner, Harold P.
Quarryville
Wilson, E. A.
Reading
Hettinger, Edwin L.
State College
Clark, David G.
Davey, Wheeler P.
Neuberger, Hans
Nitchie, Francis R., Jr.
Rank, David H.
Weyl, Woldemar
Stony Creek Mills
Grabau, Martin
Swarthmore
Kohler, Wolfgang
Swann, W. F. G.
Swissvale
Grondahl, L. O.
Leberknight, C. E.
Tarentum
Ehman, Roy G.
Towanda
Kinnear, Jean E.
Merrill, John B.
Owen, E. Robert
Parsons, S. L.
Uniontown
Eberly, Robert E.
Upper Darby
Rice, Claude K.
Wallingford
Bazzoni, Charles B.
Washington
Hill, Harry
Waynesburg
Riggs, Cecil O.
Wilkes-Barre
Policoff, William W.
Wilkinsburg
Hill, William J.
Wysox
Fisher, Dorothy C.

RHODE ISLAND—9

Kingston
Albright, John G.
Newport
Eppley, Marion
Hamilton, Russell D.
Norwood
Driscoll, Walter G.
Providence
Marshall, Albert E.
McMurtrie, Kenneth A.
Riggs, Lorrin A.
Spencer, Domina E.
Warren
Rhee, Daniel

SOUTH CAROLINA—1

Columbia
Mercer, Charles F.

TENNESSEE—10

Chattanooga
Coulliette, J. H.
Ransom, Henry
Kingsport
Otis, Marshall V.
Memphis
Anderson, Karl R.
Nashville
Slack, Francis G.
Oak Ridge
Feldman, Cyrus
Hallowell, A. Lincoln
Leslie, Elmer H.
Saunders, Bernard
Young, Clinton J. T.

TEXAS—13

Austin
Coleman, Howard S.
Coleman, Madeline F.
Harmon, Darell Boyd
College Station
Silvey, O. W.
Dallas
Yost, W. Jacque
El Paso
Weaver, W. R.
Freeport
Weddell, W. M.
Houston
Arthur, Marion A.
Johnston, Robert W. B.
Kannenstine, Fabian
MacMahon, Andrew M.
Speed, Richard H.
Lake Jackson
Perry, V. G.

UTAH—4

Provo
Marshall, Milton
Salt Lake City
Harris, F. S., Jr.
Hendley, Charles D.
Peterson, Edward F.

VERMONT—4

Northfield
Lovell, Donald J.
Pownal
Reinheimer, Hans H.
Springfield
Finn, Robert R.
Murch, Harold L.

VIRGINIA—23

Alexandria
Brown, George E.
Dember, Alexis B.
Imus, Henry A.
Laufer, Maurice K.
Packer, Donald M.
Scott, Noel W.
Arlington
Bartelt, John A.
Belknap, Marion A.
Darr, John E., Jr.
Hunter, Richard S.
London, Harry
Swanson, Mark W.
Charlottesville
Beams, Jesse W.
Brown, Frederick L.
Geldard, Frank A.
Holladay, Lewis L.
Hoxton, L. G.
Snoddy, Leland B.
Southall, James P. C.
Hampton
Bryant, Carroll W.
Hotchkiss, R. Newton
Onancock
Kollmorgen, Frederick L. G.
Richmond
Loving, R. E.

WASHINGTON—5

College Place
Kretschmar, George G.
Pullman
Abbitt, W. H.
Seattle
Cooper, F. Leonard
Freeman, Gerald O.
Vancouver
Petrey, Arthur W.

WEST VIRGINIA—9

Charleston
Williams, Dwight
Huntington
Neuhaus, C. J.
Polan, L. M.
Zenith Optical Company
Morgantown
Molby, Fred A.
Moundsville
Allen, R. Glenn
St. Albans
Ross, Joseph H., Jr.
Weirton
Geffner, Joseph
Hassell, Edward J.

WISCONSIN—9

Appleton
Davis, Myrl N.
Steele, Westbrook
Van den Akker, J. A.
Madison
Mack, Julian E.
Mote, F. A.
Stebbins, Joel
Milwaukee
Gilmour, C. A.
Poehlman, William J.
Sun Prairie
Gilroy, John

WYOMING—1

Laramie
Harding, Samuel W.

HAWAII—2

Honolulu
Belkengren, Richard O.
Holmes, W. J.

Foreign Members According to Country

ARGENTINA

Berger, C. E.
Capurro, Juan Jorge
Goodbar, Isaac
Levin, Enrique

AUSTRALIA

Esserman, N. A.
Winsor, Keith

BELGIUM

Damas, Leon
Henroteau, François C.

BRAZIL

Vasconcellos, D. F.

CANADA

Abbey, Sydney
Allen, Frank
Bateson, Sydney
Burgener, John E.
Callon, Ross William
Cave, G. C. B.
Conquergood, Charles R.
Davidson, Hedley F.
DeLury, Ralph E.
Fearnley, George
Foster, A. Willena
Frey, John G.
Gilchrist, L.
Gray, W. M.
Gustin, A. F.
Hamly, D. H.
Hazel, Wallace M.
Henderson, George H.
Howlett, Leslie E.
Ireton, H. J. C.
Jacobsen, Ratje C.
Jones, Donald C.
Laird, Elizabeth R.
Landon, Fred
Langstroth, G. O.
Lusby, G. R.
Malcolm, Scott
McLay, A. B.
Middleton, W. E. K.
Morgan, J. C.
Patterson, W. A.
Pelletier, Paul-Ed
Ruedy, Richard
Sandiford, Peter J.
Smith, H. D.
Smuck, Howard J.
Warren, Edwin W.

CHINA

Hu, Kang Fuh
Li, Norman F. C.
Loh, Hung-yu

CZECHOSLOVAKIA

Vašíček, Antonín

ENGLAND

Fleming, A. P. M.
Harrison, G. B.
Harrison, V. G. W.
Hay, O. G.
Hewitt, Joseph
Hill, N. D.
Holmes, J. G.
Horner, R. G.

Hugill, W.
Jarrold, H. John
Martin, Louis C.
Merton, Thomas R.
Taylor, A.
Taylor, Edward Wilfred
Turner, W. E. S.
Twyman, Frank

FRANCE

Castor, R. J.
Long, Bernard
Peridier, Julien
Piéron, Henri

GERMANY

Hase, Rudolph

HOLLAND

de Groot, Willem
van Heel, A. C. S.
Warsen, W.

INDIA

Banerjee, G. N.
Ghosh, Chandra Sekhar
Raman, C. V.
Rao, C. S.

ITALY

Gatterer, Alois, S. J.

MEXICO

Aguado, Alfonso Lopez
Malpica, José M.

PANAMA

Oldach, W. H.

SPAIN

Duran, D. Armando
Otero, José M.

SWEDEN

Berg, O.
Mollberg, Nils

SWITZERLAND

Goldman, Hans

VENEZUELA

Centeno, Melchor V.

Notice

Through an error the Volume Contents pages for the year 1947 were omitted from the December issue. They have been inserted at the end of this issue so that those who bind their volumes may detach them and bind them with Volume 37, 1947.